Deltares

State of the art and research trends in fluvial vegetation resistance modelling

With a focus on implementation in Rijkswaterstaat hydraulic models

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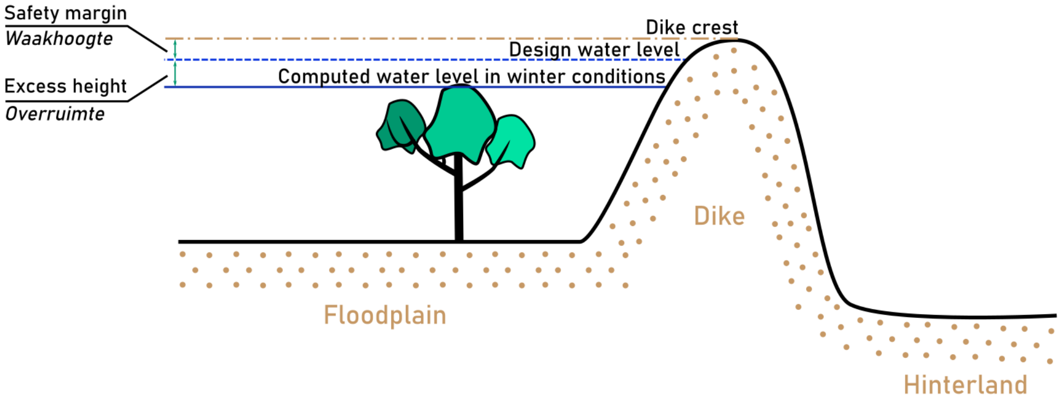
Executive Summary

Motivation

Objective
One of the tasks of Rijkswaterstaat – the executive agency of the Dutch Ministry for Infrastructure and Water Management – is the maintenance of the floodplains. As this work is largely carried out within public space, societal discussion on which function to prioritise this maintenance is not uncommon. A common critique centres on the vegetation management practices, which is perceived to be overly focussed on flood risk reduction, leading to unnecessary removal of vegetation that could otherwise serve ecological functions and values.

Floodplain management is informed by hydraulic modelling. Therefore, Rijkswaterstaat has requested a review of the way vegetation is parameterised in their hydraulic models. This review has three main objectives: (1) to describe the current practice in relation to current literature and other guidelines, (2) to interpret criticism within that context and (3) to give an overview of new scientific development that may improve Dutch practice of hydraulic modelling of vegetated areas.

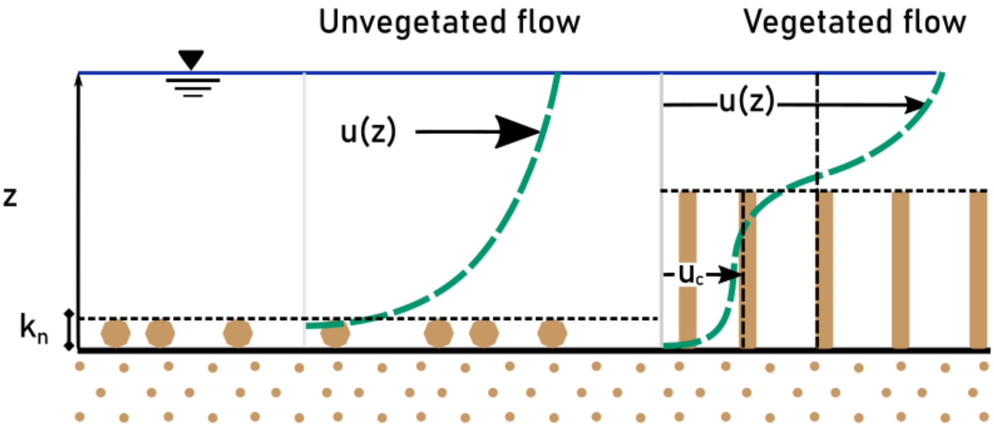
Excess height as focal point for critique
In Dutch practice, a key use of hydraulic models is the prediction of expected water levels under design conditions. These simulations in turn inform flood risk assessment studies. If these predicted water levels are lower than of critical water levels, there is excess height (Dutch: *overruimte*). This height is considered essential to allow vegetation some room to grow. In the reviewed documents, critique on current floodplain management strategies generally centres around an absence of excess height for vegetation development.



Principles of vegetated flow

Water flow through an open channel maintains a balance between discharge (flow; e.g. discharge, flow velocity) and water level (potential energy). This balance is described by the laws of motion that contain the various forces acting on the water. One of these forces is flow resistance, expressed as the Chézy coefficient. A high flow resistance causes lower flow velocities and higher water levels.

Steady flow over a sandy bed is described by a logarithmic flow profile under influence of bed shear stress near the bed. The flow resistance in this case is accurately described by the White-Colebrook formula. Approximations of this formula, such as the Strickler and Manning equations, are often used in practice. In contrast, vegetated flow forms a more complex gradient. This gradient is approximated by two-layer models, that describe flow through the vegetation layer and flow over the vegetation. Two-layer models require information on present vegetation, such as stem density and canopy height.



Representation of vegetation in national fluvial modelling guidelines

Some countries, including The Netherlands, publish modelling guidelines that consultants are required or encouraged to follow if their model study is used to support policy decisions. We reviewed published guidelines from the constituent countries of the UK, the United States of America, Australia and Germany, as well as the Netherlands, pertaining to fluvial hydraulic modelling. Within the scope of this study, it was established that such guidelines either do not exist, are not publicly available or are not generally known in Italy, France and Poland.

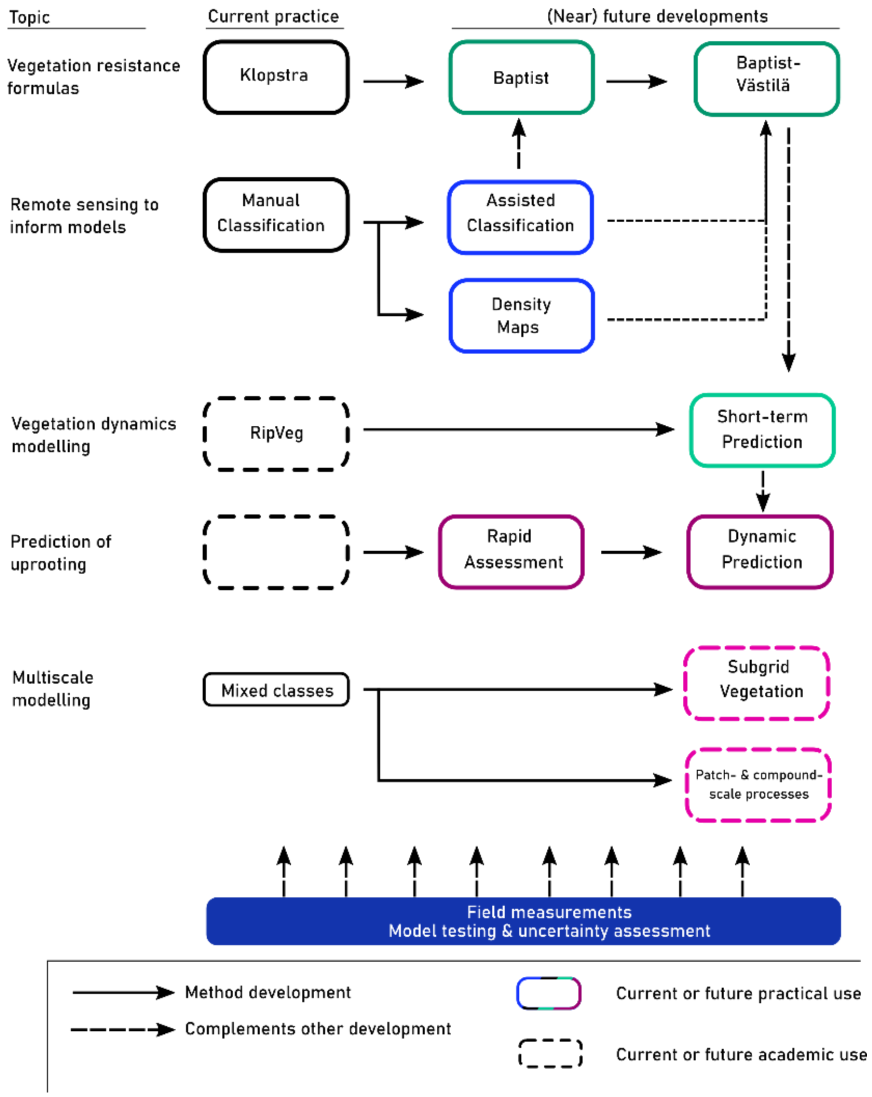
All guidelines recommend using some form of GIS-based land-use or land-cover maps to inform hydraulic models. Most guidelines recommend choosing a representative Manning value depending on the land-cover type, with the help of various look-up tables. Only the guidelines of Germany and The Netherlands recommend a two-layer model. The German guidelines are the only ones that recommend a two-layer model that accounts for some flexibility of the vegetation.

Interpreting societal critique

Based on the review of international literature, we conclude that Rijkswaterstaat employs state-of-the-art methods to resolve the effect of vegetation in hydraulic models and is well positioned to take advantage of scientific innovations (itemized below). However, this relatively detailed approach, while state-of-the-art, should not necessarily be confused with high accuracy. While these methods are more accurate to other approaches in theory, significant uncertainty remains, especially at extrapolation to higher discharges and the effect of (seasonal) changes to the system.
We advise Rijkswaterstaat to explore the possibilities outlined in this report to build on and further improve its methods to account for natural vegetation development within the bounds of a predicted excess-height. This approach may both benefit current management practices in the context of seasonal vegetation, as well as potential future management, as it moves towards integrated, sustainable management of the river system.

Trends in vegetation research to benefit Dutch practice

Based on a brief review of (scientific) literature and research partnerships of Deltares, we identified five main fields of development and two supporting fields. We summarized the current practice for these fields and potential future improvements in the following roadmap. Below, we itemize these steps related to their relative technological maturity, and give concrete advice how Rijkswaterstaat could move forward on these topics.



Close-to-practice improvements

Steps that are scientifically and technologically ready for implementation but may require additional testing or adaptation to fit within current guidelines are the adoption of the Baptist flow resistance formula and the use of assisted classification maps to inform hydraulic models more frequent (e.g. annually).

We advise to assess the impact on model results of switching to the Baptist equation for vegetation resistance, especially when extrapolating beyond calibrated (and measured) ranges of observed water levels and discharge. Such a study could address how to modify current handbook (*Stromingsweerstand vegetatie in uiterwaarden;* van Velzen, 2003*),* parameters, the effect of recalibration on discharge distribution between floodplain and main channel, predicted water levels and the assessment of intervention effects. Furthermore, we advise to formulate acceptance requirements for the accuracy of assisted classification maps. Assisted classification concerns methods that incorporate machine learning (e.g. *vegetatiemonitor,* see chapter 4.1) as well as other information (e.g. management plans, see chapter 4.3.3) with the aim of increasing the frequency of vegetation map updates.

Technological development

Steps that have a broad or growing scientific basis but require further technological development or specific Dutch case studies, are the use of remote sensing density maps (such as Leaf Area Index maps) and flow formulas that incorporate reconfiguration (flexible vegetation).

We advise a study of satellite derived density maps (e.g. based on the leaf-area index) for the Dutch rivers over a period of multiple years, with the aim of observing the long-term and seasonal trend in vegetation density. The results can already be compared to international literature, as well as to the current values in the national guideline (‘*Handboek vegetatieruwheid*’; van Velzen et al., 2003b). This study should provide insight in the applicability and feasibility of using satellite derived LAI-density maps, as well as the potential influence on model results. Building on this, we advise to study the potential benefit of using the Baptist-Västilä formula variant to model summer vegetation. Such a study should address the sensitivity of the reconfiguration parameters in Dutch rivers, and if necessary, derive parameter values specific to species characteristic to the Dutch floodplains. Finally, the sensitivity of, and potential candidates for canopy deflection models should be addressed.

Scientific demonstration

Steps that are proposed but require a broader evidence base in literature are rapid assessment of uprooting, subgrid vegetation representation and prediction of vegetation dynamics. Patch- and compound-scale processes are still being studied academically. To our knowledge, no potential candidate method to improve current practice has been proposed or tested.

While relatively simple uprooting models are proposed, to our knowledge evidence of uprooting is only anecdotally available. We advise to enquire with relevant regional experts what sites are known to be susceptible to uprooting after a significant flood, and to start logging evidence of uprooting, after a flood occurs through photographs and GIS maps. Such evidence is important to be able to validate future models. For multiscale modelling we advise to invest in upscaling current computer- or lab experiments to (near) field conditions. Water level measurements alone may not provide enough information to confidently validate method improvements. Field measurements, especially during floods, are invaluable to establish more confidence in extrapolating model results to unseen conditions.

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Table of symbols

Symbol	Unit	Description
κ	$-$	von Kármán constant.
ξ	m	Water level above a reference plane (e.g. MSL; mean sea level, NAP; Normaal Amsterdams Peil)
ρ	$kg.m^{-3}$	Mass density
τ_b	$kg.m^{-3}$	Bed shear stress
τ_t	$id.$	Total shear stress
A_f	m^2	Area of a cross-section that conveys flow
C	$m^{\frac{1}{2}}s^{-1}$	Chézy coefficient
C_b	$id.$	Chézy coefficient of the bed
C_D	$-$	Drag coefficient
D	m	Vegetation stem diameter
f	$-$	Darcy-Weisbach coefficient
f'	$id.$	Darcy-Weisbach coefficient, bed shear stress component
f''	$id.$	Darcy-Weisbach coefficient, vegetation component
g	$m.s^{-2}$	Gravitational acceleration
h	m	Water depth
h_d	m	Deflected vegetation, stem or canopy height
h_v	$id.$	Vegetation, stem or canopy height
i_b	$m.m^{-1}$	Bed slope
K	$m.m^{-1}$	Submergence ratio, defined as h/h_v
k_N	m	(Nikuradse) roughness height
m	m^{-2}	Number of stems per square metre
n	$s.m^{-\frac{1}{3}}$	Manning coefficient
R	m	Hydraulic radius
u_v	$m.s^{-1}$	Flow velocity in vegetation or canopy layer
$\bar{u}$	$m.s^{-1}$	Cross-sectionally averaged flow velocity
u	$m.s^{-1}$	Flow velocity
q	m^2s^{-1}	Specific discharge
Q	m^3s^{-1}	Discharge

1 Introduction

1.1 Motivation

Rijkswaterstaat is the executive agency of the Dutch Ministry for Infrastructure and Water Management. One of its tasks is the maintenance of the floodplains of the major rivers.

According to Rijkswaterstaat, the team responsible for floodplain management (*Team Uiterwaardenbeheer;* Taskforce for Floodplain Management) regularly receives societal critique regarding the underlying arguments used to justify maintenance decisions and maintenance works. On the one hand, vegetation may obscure people's view on the river and be perceived as unsafe due to obstruction in case of a flood. On the other hand, the effect of vegetation on water levels is argued to be overestimated by Rijkswaterstaat, leading to unnecessary removal of vegetation that could otherwise serve ecological functions. This amount of resistance vegetation offers to flow and the magnitude of the resulting backwater is a key topic in these discussions.

1.2 Scope

For this reason, Rijkswaterstaat asked Deltares to give an overview of the current state-of-the-art on how vegetation resistance is resolved within hydraulic models in leading guidelines, within the scope of the societal critique, and to identify current scientific insights that could lead to an improvement of the current practice of Dutch floodplain maintenance.

The scope of this report is therefore limited to the hydrodynamic aspects of vegetation, i.e. vegetation as a source of flow resistance, in fluvial modelling practice (1D and 2D modelling).

1.3 Societal critique of floodplain management

The discussion on the perceived trade-off between flood safety and ecological functions is not new, but a recent publication by the World Wildlife Fund ("Flows Productions" & "WWF," 2021) has rekindled this argument. In this section, we summarize the arguments put forward by WWF and others insofar that they relate to vegetation modelling at Rijkswaterstaat. The purpose of this summary is not to refute or rebut arguments, but to assess them in the context of the current state-of-the-art for the purpose of furthering of the Dutch practice. If published rebuttals to societal critique are available, we discuss them as well.

The final outcome of trade-offs between potentially conflicting benefits is ultimately political and not a subject of the current report. This report aims to support this (political) discussion, not decide it.

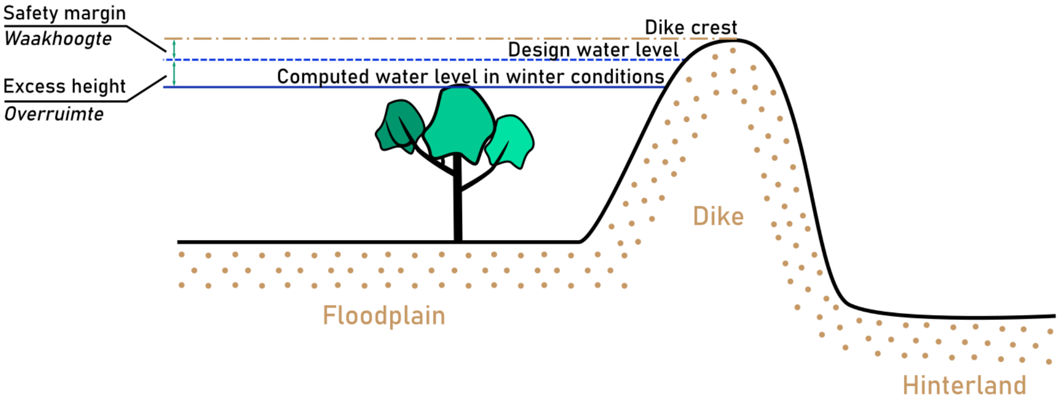

Figure 1.1 The excess height is a measure for how the river can deviate from design conditions. Without any excess height, any deviation from design condition may lead to exceedance of the critical water level.

We consider three main lines of argumentation related to vegetation modelling in general and the excess height (Dutch: *overruimte*) specifically. The excess height is a term generally meant to understand a height (in centimetres) difference between the design water level and the computed water level at design discharge (Figure 1.1; Peters, Kater, and Geerling 2006). This is different from the safety margin (Dutch: *Waakhoogte*), which main purpose is to account for wave overtopping. Here, the critical water level is understood to mean some condition at which an unacceptable risk to society occurs. The design conditions refer to the state of the river (including vegetation cover) at design discharge(s). The general critique is that there is an absence of excess height to allow for vegetation dynamics, e.g. the growth and succession of vegetation.

Various societal groups have suggested ideas to improve this situation. Their lines of argumentation can be categorised as follows.

1 | There is more excess height than computations show, because of conservative assumptions in vegetation resistance formulations

Querner and Makaske (2011), writing for the former research institute Alterra[1], argued that the methods prescribed in the official guidelines may overestimate the influence of vegetation on water levels. Their arguments centre on the specific formulas for vegetation resistance, which are discussed in chapter 2, as well as on conflating various sources of roughness into

> *"If the current guidelines overestimate the roughness of, for example, grass lands and herbaceous meadows, then the actual 'room for nature' is larger than is currently assumed based on model simulations. In that case, we would not need additional measures to create 'room for nature'.*
>
> *"Indien het handboek vegetatieruwheid de ruwheden van bijvoorbeeld graslanden en ruigtes zou overschatten, is het mogelijk dat de feitelijke ruimte voor natuur groter is dan nu, op basis van de modelberekeningen, wordt verondersteld. In dat geval zouden extra rivierkundige maatregelen ten behoeve van riviernatuur niet nodig zijn"*
>
> Querner and Makaske (2011)

---

[1] Alterra has since merged with Wageningen University & Research as Wageningen Environmental Research (WER)

‘vegetation roughness’. Their argument was rebutted by Mosselman and van Velzen (2011), who argued (a) that the chosen approach is suitable for the Dutch situation, albeit maybe not for other situations, (b) that model simulations compare favourably with measurements under the current assumptions and (c) that the projected additional excess height does not take into account model calibration.

The Alterra report is reportedly (informally) often still named as a source of critique. Given this, and the time since this exchange, it is worthwhile to reconsider the arguments on both sides. We discuss the background of flow resistance, specific formulas and model calibration in chapter 2. Official guidelines on how to deal with vegetation in hydraulic models are discussed in Chapter 3.

2 | The effect of seasonal vegetation is overestimated or too uncertain

In the summer of 2021, heavy rainfall led to disastrous flooding in Belgium, Germany and The Netherlands. On the Meuse, water levels rose to never-before recorded heights. This event was rare[2], not only because of its severity (160-180 mm in a two-day period), but also because it took place in summer (Task Force Fact-finding hoogwater 2021, 2021). In the upper reach of the Dutch Meuse river, water levels were very high, although no fluvial flooding took place along the Meuse in The Netherlands.

Following these events Rijkswaterstaat announced maintenance of the floodplains to improve conveyance. However, Rijkswaterstaat is not the (sole) owner of the land in the floodplains. In the Netherlands, ownership of the floodplains is often divided amongst thousands of landowners (Fliervoet & van den Born, 2017). One of these landowners is the nature conservation organization *Vereniging Natuurmonumenten*, who commissioned a study whether vegetation was a key contributor to high water levels (Bureau Stroming, 2021).

> *“Shortly after the flood event fingers were pointed at vegetation as the main cause of the unexpectedly high water-levels. It was assumed that the flow resistance was higher than projected due to the fact that it was summer – there was foliage on the trees and certain plants had grown higher than assumed for winter conditions. This idea immediately led to an announcement by Rijkswaterstaat to remove all vegetation that does not conform to design conditions”.*
>
> ---
>
> *“Al snel na het hoogwater werd de ruwere vegetatie als oorzaak aangewezen voor de hogere waterstanden. Omdat de bomen nu in blad staan en kruiden en ruigte hoger zijn, is de weerstand hoger en dat zou de hogere waterstanden moeten verklaren. Dit idee leidde er al meteen toe dat Rijkswaterstaat aankondigde om vegetaties te gaan verwijderen die buiten de in de legger aangegeven gebieden staan”*
>
> (Bureau Stroming, 2021)

This study noted that water levels were higher than expected based on stage-relation curves (Dutch: *Betrekkingslijnen*). Bureau Stroming (2021)argued that this was not due to vegetation – as was mentioned in public discourse – but to progressive embankment of the floodplains. However, their analysis was refuted by Schropp (2021), who criticized both their initial analysis using stage-discharge relation curves as well as their conclusion. However, it should be noted that the Expertise Network for Water Safety (ENW) also noted up to 60 cm higher

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[2] Estimates range from a 100 to a 1000 year event (Task Force Fact-finding hoogwater 2021, 2021)

water levels during the summer flood compared to established stage-relation curves (Task Force Fact-finding hoogwater 2021, 2021).

Whether or not the higher water levels are partially attributable to vegetation, the take-away message from this critique is that it is unknown how much excess height (Figure 1.1) there should be to account for seasonal vegetation. This uncertainty leaves room for discussion and disagreement. In section 4.2 we will discuss model studies carried out to assess the effect of summer vegetation and current trends in scientific progress on this topic.

3 | There is no excess height, but it can be created at relatively little expense compared to the benefits it brings in terms of natural values

A final line of 'critique' is voiced by the online report "Vertical Room for the River" ("Flows Productions" & "WWF," 2021). Their objective is to create more dynamic nature, which they define *as nature that may freely develop without being constrained by concerns about hydraulic roughness* (Dutch: *natuur die zich zonder beperking door hydraulische ruwheidseisen mag ontwikkelen*). They propose extensive (meaning less or no) vegetation management, which is compensated by raising the *design water level* (Figure 1.1) by dike reinforcement at key locations[3].

> *"Floodplain vegetation is mowed and cut down to prevent centimetres of backwater, because this increases the risk of flooding. But how large is this effect really? (..) Studies show that the additional backwater due to vegetation costs relatively little in terms of extra dike reinforcement".*
>
> ---
>
> *"Vegetatie in de uiterwaarden wordt gekapt en gemaaid om centimeters opstuwing te voorkomen. Opstuwing vergroot immers de overstromingskans. Maar hoe groot is dat effect eigenlijk? (…) Uit onderzoek door HKV voor deze productie blijkt dat opstuwing door riviernatuur relatief weinig kost aan extra dijkversterking."*
>
> ("Flows Productions" & "WWF," 2021)

Their argument rests on the assumption that raising the water levels with 10 cm in key locations leads to significant ecological benefits. The risk analysis was carried out by Oerlemans and Caspers (2021). However, no (new) hydraulic simulations were carried out to determine the effect of vegetation on water levels. Instead, the authors refer to simulations carried out within the government study on ecological system analysis in the context of PAGW-Rivieren[4] (Heusden et al., 2021). Therefore, it is unclear how the benefits of "Vertical Room for the River" will materialize, i.e. how much nature 10 cm will buy.

In contrast, the PAGW-Rivieren study maps out the required vegetation cover to meet ecological goals in 2050. The effect of this vegetation cover on water levels has been assessed by HKV (2020). They project local increases of up to 35 cm on the IJssel and 25 cm on the Waal for design discharge. PAGW-Rivieren proposes to meet this target by increasing the capacity of the channel by 'Room for the River' type interventions (so by

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[3] The discussion on whether the costs associated with dike reinforcement (and potential buy-out of landowners, which the report does not mention) off-set the additional ecological benefits is not within the scope of this report. Instead, we focus on the technical argumentation and on the question to what extent the current state-of-the-art supports such an analysis.

[4] PAGW = "Programmatische aanpak Grote Wateren" ("*Planned approach for large water systems"*), is an inter-ministerial collaboration aimed to improve water quality & ecology for 2050. See https://www.pagw.nl/

decreasing the ‘computed water levels’ in Figure 1.1). In this context, it is unlikely that a 10 cm increase on key locations, proposed by “Vertical Room for the River” publication (“Flows Productions” & “WWF,” 2021), will be enough to reach the goals set out by the arguably more ambitious PAGW-Rivieren. Nonetheless, both initiatives argue to include ecological goals as an important driver in designing the future of the Dutch river system.

1.4 Objectives

Taking the above considerations of paragraph 1.3 into account, Rijkswaterstaat has asked Deltares to answer the following questions:

1 What are the main principles to model vegetation in hydrodynamic models?
  a Which formulas, approaches or models are commonly used and what are the main differences between these models?
  b What is the current practice within Rijkswaterstaat, what are the underlying assumptions or principles, and how does this relate to current practices from literature?
2 What is the merit of the critique on Rijkswaterstaat regarding vegetation modelling?
3 Which scientific insights can lead to an improvement of the current practice?
  a How, and in which time frame, can these insights be incorporated in currently used models?
  b What are the potential consequences for floodplain management and maintenance works within Rijkswaterstaat?

1.5 Team

Deltares has consulted the following people in writing for this report, each considered expert in their respective field.

Name	Institute	Role
Dr. ir. Koen Berends	Deltares	Lead author
Dr. Aukje Spruyt	Deltares	Co-author Dutch model instrumentarium
Dr. ir. Jasper Dijkstra	Deltares	Co-Author Subgrid modelling, coastal modelling and NBS Dynamics
Dr. Melissa Latella	Politecnico di Torino	Co-Author Remote sensing
Dr. ir. Erik Mosselman	Deltares	Reviewer Fluvial hydromorphodynamics
Dr. Ellis Penning	Deltares	Reviewer Ecology and Nature-Based Solutions
Dr. Giulio Calvani	Ecole Polytechnique Fédérale de Lausanne	Expert Uprooting of vegetation
Dr. Mijke van Oorschot	Deltares	Expert Vegetation dynamics
Dr. Ralph Schielen	Rijkswaterstaat WVL	Client, problem owner
Ir. Rick Kuggeleijn	Taskforce Floodplain Maintenance	Client, problem owner
Drs. Rik van Neer	Rijkswaterstaat Oost Nederland	Client, problem owner
Prof. dr. ir. Wim Uijttewaal	Delft University of Technology	Expert Environmental fluid mechanics

Name	Institute	Role
Dr. Juha Järvelä	Aalto University	Expert Flexible vegetation
Dr. Kaisa Västilä	Aalto University	Expert Flexible vegetation
Dr. Luca Solari	University of Florence	Expert Woody debris flow
Dr. Gertjan Geerling	Deltares	Expert Cyclic rejuvenation

1.6 Reader's guide

We structured this report in four different sections. In chapter 2, we give a brief overview of the principles of modelling vegetated flow. We discuss the basic equations governing open channel flow and the various paradigms for considering vegetation. In chapter 3 we discuss the operational state-of-the-art, meaning official guidelines for practical fluvial modelling. We discuss the practice at Rijkswaterstaat, and then review recent official guidelines from either governmental agencies or leading non-governmental agencies from various countries to compare the Dutch practise to those of other countries. In chapter 4, we review the state-of-the-art in science on topics selected from discussion with leading experts (see section 1.5). The purpose of this chapter is to identify potential developments for Rijkswaterstaat to incorporate into their methods. Finally, in chapter 5, we synthesize the results and give advice for future work.

2 Principles of modelling vegetated flow

This chapter briefly outlines the most important terms required to understand the discussion in this report. We will introduce the terms “roughness”, “friction”, “shear stress” and “drag”, which are related and often used interchangeably.

2.1 Hydraulic roughness

2.1.1 Flow resistance

In practical applications, one of the key benefits of hydrodynamic modelling is its power to determine the relationship between the water flow through a river (expressed as total discharge in m^3s^{-1}, specific discharge in m^2s^{-1} or flow velocity in $m.s^{-1}$) and the water level (water surface elevation in m), given the layout of the water system.

This relationship follows from the Navier-Stokes equations – the universal mathematical model for fluid mechanics. However, open-channel flow is often sufficiently described by a subset of these equations. For fluvial applications within the scope of this report (hydraulic simulation of river flow on a scale of 100 km), this subset consists of the shallow-water equations. These equations omit or simplify certain processes – such as turbulence modelling and vertical distribution of flow velocities – to the benefit of computational efficiency, under the assumption that the horizontal length scale (e.g. river width) is much greater than the vertical length scale (water depth).

For the purpose of this report, an important simplification is lumping various processes that lead to energy loss into at least one term in the momentum equation. This term is usually termed *flow resistance*. The one-dimensional shallow-water momentum equations can be written as follows:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right) + \frac{g A_F \partial \xi}{\partial x} + \frac{g Q|Q|}{C^2 R A_F} = 0 \qquad (1)$$

with discharge Q [m^3s^{-1}], cross-sectional conveyance area A_F [m^2], water level above reference datum ξ [m], hydraulic radius R [m], gravitational acceleration g [$m.s^{-2}$], Chézy coefficient C [$m^{1/2}/s$], time t [s] and space x [m]. This equation describes the balance between (from left to right):

1 Inertia: an acceleration in the form of a change in discharge in time
2 Advection: an acceleration related to changes of fluid motion through space
3 Gravity: force acting on fluid due to differences in water level
4 Resistance: counterforces reacting on flow in response to movement

This fourth term is key to our understanding of the role of vegetation in hydrodynamic modelling, because vegetation is commonly considered as a source of flow resistance[5].

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[5] Note that the effect of vegetation on ‘*blockage’* – effectively reducing the cross-sectional flow area (or hydraulic radius) – is indirectly factored into flow resistance for most (fluvial) modelling studies.

2.1.2 Sources of flow resistance

The fourth term in equation (1) expresses the total resistance to flow in one term. It is related to shear stress (and expressed in terms of depth-averaged flow velocity) as follows:

$$\frac{g\bar{u}^2}{C^2R} = \tau_t\rho^{-1} \qquad (2)$$

with depth-averaged flow velocity $\bar{u}$ [m.s^{-1}], total shear stress τ_t [kg.s^{-2}] and density ρ [kg.m^{-3}]. In one- and two-dimensional applications to wide rivers, the hydraulic radius is replaced by the water depth. In this equation (2) the Chézy coefficient parameterizes the “amount of resistance” to flow. This term is sometimes, somewhat erroneously, called the ‘bed friction’. However, the term generally models many (if not all) sources of resistance, including but not limited to bed friction. For the purpose of vegetation modelling, it is useful to distinguish two broad sources of flow resistance: resistance due to flow velocity gradients and resistance due to pressure gradients.

The first is resistance due to shear stresses, which follow from local differences in flow velocity. The contact with the bed generates shear stresses that leads to a vertical profile of flow velocities. The flow velocity at the bottom of the channel is zero and it then increases toward the water surface in a logarithmic profile (Figure 2.1). The shear stress is a source of flow resistance. The bed material influences the development of this logarithmic profile.

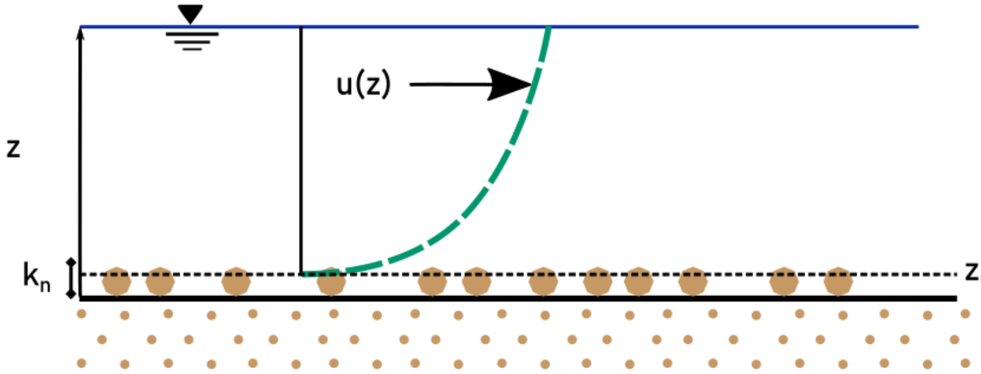

Figure 2.1 The flow profile over a hydraulically rough bed can be approximated by a logarithmic curve. Adapted from (van Rijn 1990)

Likewise, in horizontal direction flow velocities are zero near the banks of the river (or other obstacles) and increase toward the middle. In one-dimensional models, these horizontal shear stresses are included in the lump term as well. In two-dimensional models, these horizontal stresses are modelled using a horizontal eddy viscosity term.

The second broad term of flow resistance is due to difference in pressure. In the wake of obstructions, a low-pressure zone may form that acts as a force on both the object and the flow. This is commonly referred to as *drag resistance*. Examples of objects that generate drag are bed forms (e.g. river dunes), plants and other (anthropogenic and non-anthropogenic) objects.

In most hydrodynamic models, these two broad categories are both modelled using the ‘bed friction parameter’ or ‘bed shear stress’. However, one should keep in mind that the ‘bed friction’ represents more sources of resistance than just those generated at the bed.

2.2 Models for flow resistance

2.2.1 Units of friction

Equation (2) expresses the bed shear stress as a function of the Chézy coefficient. This coefficient predates the Navier-Stokes equations by more than half a century. Halfway the 18th century, it was discovered that the water level was related to discharge by the square of the bed slope (Velsen, 1749). Antoine de Chézy formalized this in what is considered to be one of the first flow formulas including a resistance term (Benito et al., 2015; Chézy, 1775, 1776):

$$\bar{u} = C\sqrt{Ri_b} \tag{3}$$

with bed slope i_b [m/m]. It can be easily proven that equation (3) – known as Chézy's equation – is a simplification of the shallow-water momentum equation (1) if one assumes steady flow (inertial term goes to zero) and uniform flow (advection term goes to zero; bed slope is equal to the slope of the water level). Refactoring the remaining terms yields Chézy's equation.

There are two major disadvantages to Chézy's coefficient. The first disadvantage is that it has a rather unwieldy unit ($m^{1/2}s^{-1}$). A dimensionless alternative is the Darcy-Weisbach factor f [-], which is related to the Chézy coefficient as follows:

$$f = \frac{8g}{C^2} \tag{4}$$

Both Chézy's coefficient C and the Darcy-Weisbach factor f can be considered metrics of resistance, and we shall see that many friction models express their effect on flow in terms of these coefficients. In this report, we express roughness exclusively in relation to the Chézy parameter.

The second major disadvantage is that the Chézy coefficient (idem Darcy-Weisbach) is not a constant but known to vary with water depth and flow velocity. This leads to a plethora of *friction models* that predict the value of Chézy's coefficient. These models are discussed in the following chapters.

Going forward, it is interesting to note that there is only slow (if any) convergence of flow resistance equations in practice. Perhaps owing to both the empirical nature of flow resistance and its immense importance for practical applications, cultural legacy as much as positivistic arguments determine which formula prevails in practice[6]. In the Netherlands, Chézy's coefficient is generally used as the basic unit of roughness. In this report, we will follow this custom. In the United States of America, Darcy-Weisbach's f is more prevalent (van Rijn 1990).

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[6] Similar behaviour has been found in hydrology (Addor & Melsen, 2019)

2.2.2 Friction models for hydraulically rough flow

The first class of friction models describes the resistance that leads to the logarithmic flow profile (Figure 2.1). These flow profiles themselves were based on experimental data (Nikuradse, 1931) on a wide range of conditions. The general formula that describes this is the White-Colebrook (also known as Colebrook-White) formula (Colebrook and White 1937), which reads as follows for hydraulically rough flow[7]:

$$C = 18 \log \frac{12R}{k_n} \tag{5}$$

in which k_n [m] is the Nikuradse roughness height. This formula is alternatively known as the Keulegan equation (Augustijn et al., 2008; Keulegan, 1938). Another formula is Strickler's (1923) formula that, while it predates the formulae of Colebrook and White, approximates Colebrook and White (Figure 2.2). Strickler's approximation is:

$$C = 25 \left(\frac{R}{k_n}\right)^{0.166} \tag{6}$$

With current computational power, there is no reasonable argument to use Strickler's approximation anymore, and its use should generally be strongly discouraged.

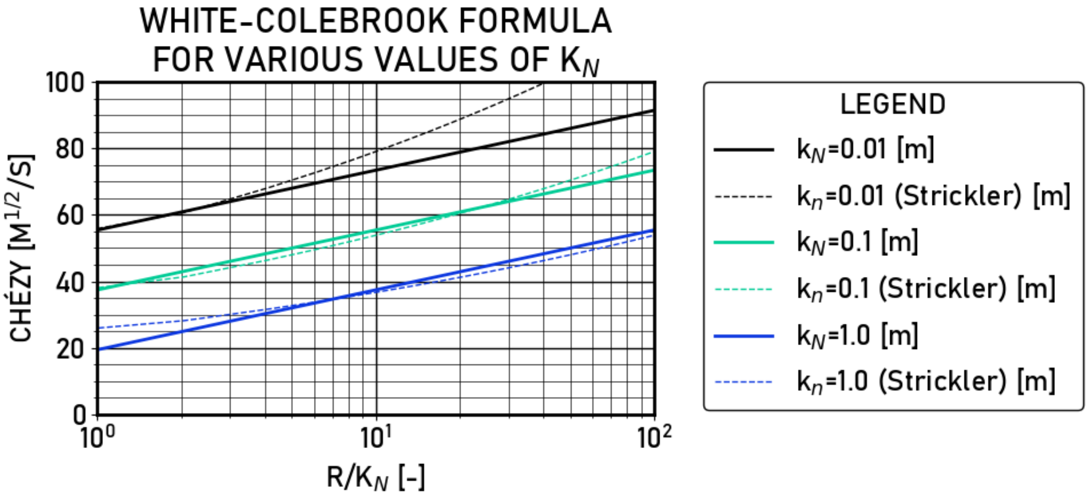

Figure 2.2 The value of the Chézy coefficient for various values of k_n using the White-Colebrook equation (5) and the Strickler equation (6). Expanded reproduction of figure 6.5.2 from (van Rijn 1990).

A third general formula for roughness is Manning's formula, which reads:

$$C = \frac{R^{\frac{1}{6}}}{n} \tag{7}$$

with Manning coefficient n (s.m$^{-1/3}$). Like Strickler's formula, it predates White and Colebrook. The relationship between C and the sixth root of R was presumably independently proposed by Gauckler (1868), Hagen (1881) and Manning (1891). In practice, the inverse root of n, known informally as Manning's k, is also used. Notice the similarity between the Manning and Strickler formula is such that n can be approximated by $n = 0.04 k_n^{\frac{1}{6}}$. Therefore, the Manning formula can also be seen as an approximation of the White-Colebrook equation.

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[7] In river modelling, hydraulically rough flow can be safely assumed.

Manning's formula is extremely well-known, to the point that it is a default formula for most applications, despite its purely empirical nature. This popularity cannot be disentangled from the numerous look-up tables for the Manning coefficient, such as Chow (1959) and Cowan (1956), which made it relatively easy to choose a roughness value given the type of stream (e.g. 'natural stream', 'medium brush'). Once established, the pressure of cultural legacy ensured that Manning's *n* has become a default 'lumped roughness parameter' in many applications.

However, at its heart Manning's equation approximates White-Colebrook, which itself is only applicable for a certain type of flow with a well-established logarithmic profile. For other types of flow, such as flow over bed forms (e.g. river dunes[8]) and flow through and over vegetation, neither formulae are (theoretically) adequate.

2.2.3 Two-layer models for vegetation friction

Vegetated flow generally does not have the logarithmic flow profile of unvegetated streams (Figure 2.1), which is why formulas such as White-Colebrook and Manning are theoretically less well suited for these applications. Figure 2.3 shows a typical vertical flow profile for *submerged vegetation*, i.e. conditions where the flow depth h is larger than the vegetation height h_v. The ratio h/h_v is called the *submergence ratio.* In literature, equations have been proposed to predict the roughness coefficient for both *emergent vegetation* ($h<h_v$), submerged vegetation ($h>h_v$) and both regimes (i.e. in a single formula).

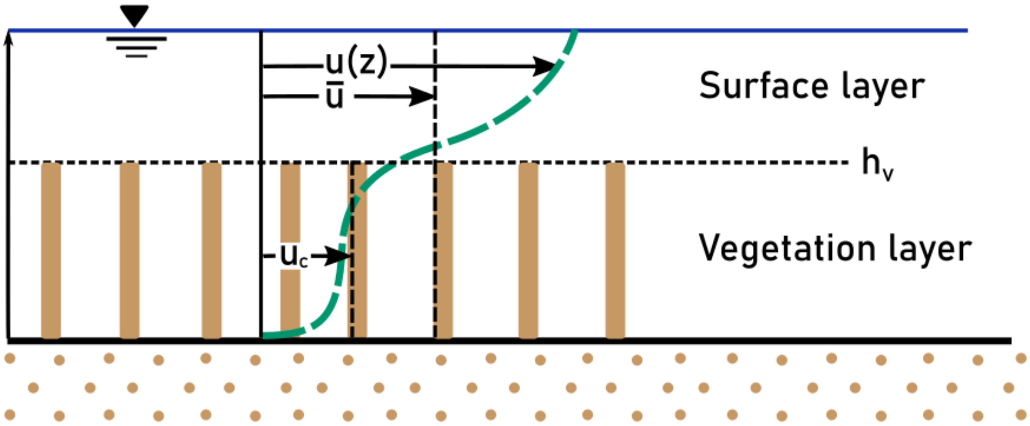

Figure 2.3 Typical flow profile for submerged vegetation, with canopy height h_v [m], velocity profile u(z) [m.s^{-1}], depth-averaged velocity $\bar{u}$ [m.s^{-1}], and average velocity through the vegetation layer u_c [m.s^{-1}].

From the distinction between emergent and submerged flow conditions, it is natural to think of the flow profile in Figure 2.3 as consisting of two different layers. Most models therefore approach this as a 'two-layer problem' and focus on establishing a smooth transition from emergent to submerged flow conditions.

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[8] These equations will not be discussed in this report, but interested readers are referred to (van Rijn 1993; Vanoui and Hwang 1967; Noori and Smith 1984; Wright and Parker 2004; Warmink, Booij, et al. 2013)

In the past decades, many models have been proposed and tested against lab experiments. In these lab experiments, vegetation is generally simplified as rigid cylinders (e.g. nails) with varying spacing (*s* – or number of stems per unit area *m*), diameter (*D*) and height (h_v). Under lab conditions, the drag coefficient (C_D) of these vegetation approximations can be accurately measured. This growing database of lab experiments is used as a benchmark between various competing two-layer models (Figure 2.4), that take the variables from above experiments as input. For example, the formula proposed by (Baptist et al., 2007):

$$C = \left(C_b^{-2} + \frac{mDC_Dh_v}{2g}\right)^{-\frac{1}{2}} + \frac{\sqrt{g}}{\kappa}\ln(K) \qquad (8)$$

with von Kármán constant κ [-], Chézy bed roughness C_b [$m^{1/2}/s$] and submergence ratio *K* [m/m]. The first right-hand term describes the roughness of the emergent flow, while both right-hand terms together describe submerged flow. We shall see later that this formula collapses to the White-Colebrook formula under submerged conditions (Augustijn et al., 2011) and to Chézy for emergent conditions.

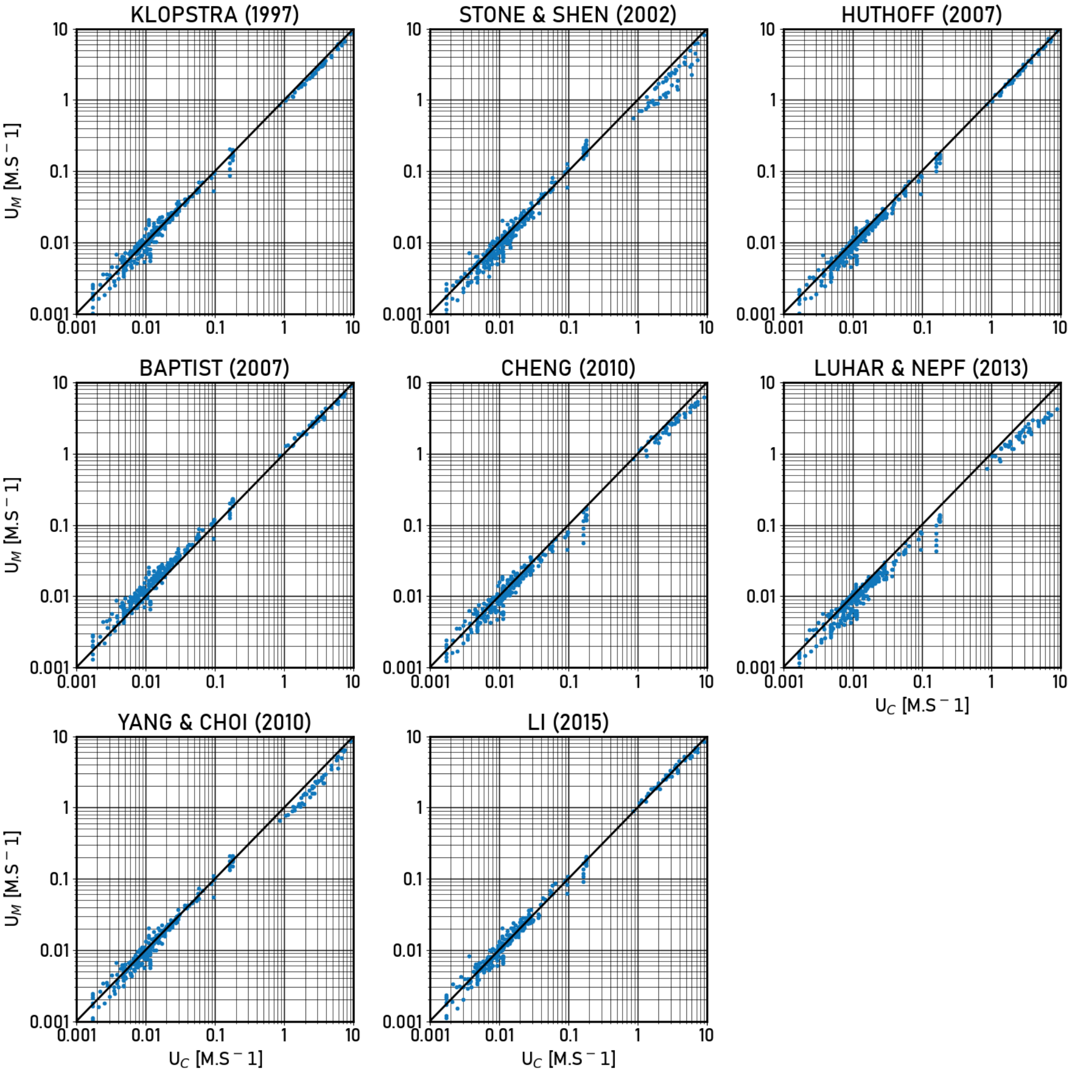

Figure 2.4 A benchmark of two-layer models, with on the horizontal axis predicted flow velocity (u_c), and on the vertical axis measured flow velocity (u_m). Reproduction based on data from (Li et al., 2015)*, using formulas:* (Baptist et al., 2007; Cheng, 2011; Huthoff et al., 2007; Klopstra et al., 1997; Luhar & Nepf, 2013; Stone & Shen, 2002; Yang & Choi, 2010)*. All models seem to perform well on this dataset. The formulas for the Klopstra and Baptist formulas are written out in Appendix A.*

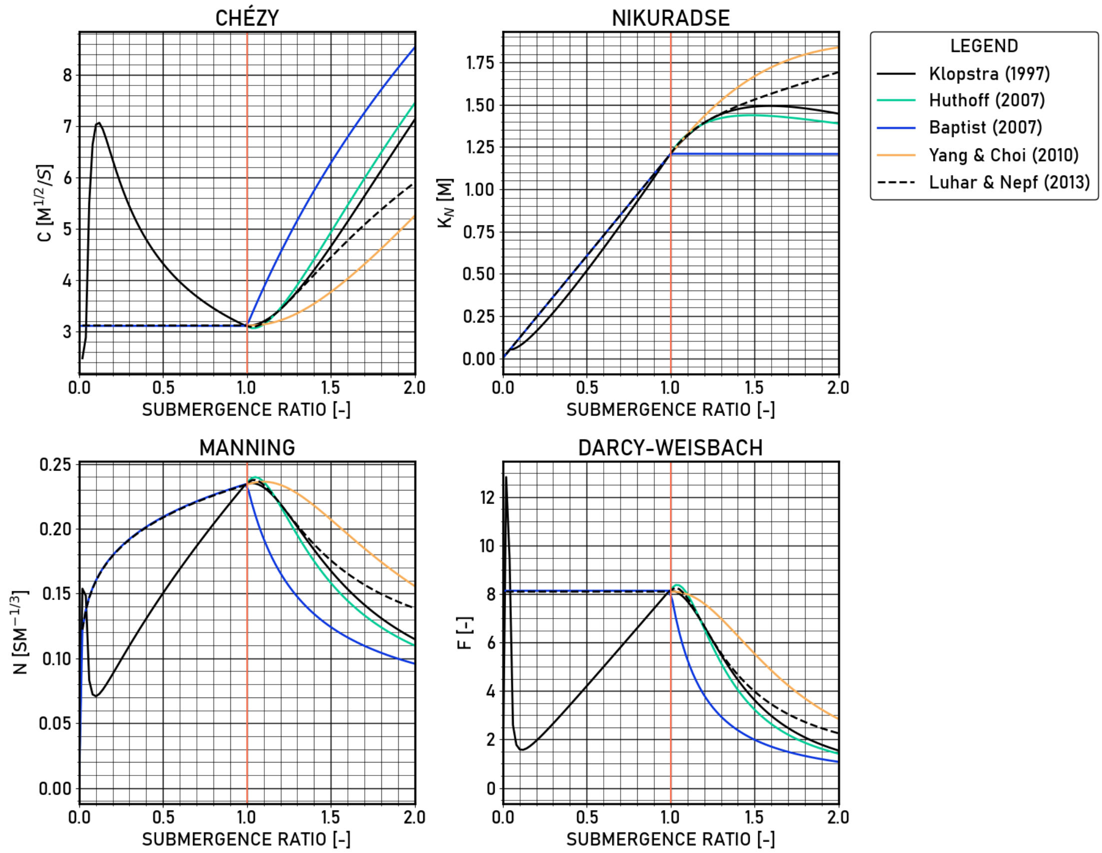

Figure 2.5 The result of various friction models, expressed in four base metrics of friction.

However, these benchmarks do not necessarily give a good indication of their accuracy and behaviour under real-world conditions. It is illustrative to compare how these two-layer models compare to the basic metrics of roughness. For the purpose of this illustration, we reproduce the case discussed by Augustijn, Galema, and Huthoff (2011), and expand it to the emergent regime, also adding the formula of Luhar & Nepf.

Figure 2.5 shows the result of five different vegetation formulas, using the parameter settings for 'natural grassland' $[h_v = 0.15\ \mathrm{m}, D = 0.003\ \mathrm{m}, m = 4500\ \mathrm{m}^{-2}\ C\_D = 1]$. Two of these models (Huthoff et al. and Yang & Choi) are models for submerged flow only.

For these equations, we observe quite different behaviour. In emergent conditions (submergence ratio < 1), the Baptist formula reduces to a constant Chézy value. This is readily derived from equation (8), where the first right-hand term is independent of the water depth. The formula of Luhar and Nepf (2013) shows similar behaviour. Only the Klopstra formula is water level dependent under emergent conditions – although it tends to show unexpected behaviour at very low submergence ratios.

In the submerged regime, all models predict a decreasing roughness with increasing submergence ratio, with the Baptist model showing the 'smoothest' model and the Yang & Choi model the roughest. The Baptist model reduces to a constant k_n value under submerged conditions. The equivalence between Baptist and White-Colebrook can easily be derived from equation (8).

In literature, the Baptist formula is one of the most widely used formulas for vegetated flow (Vargas-Luna, Crosato, and Uijttewaal 2015; Warmink et al. 2011; Berends et al. 2018), and has been adopted in most computational frameworks.

2.3 Calibration, sensitivity and uncertainty analysis of friction in compound channel flow

In practice, river models do not compare well enough to measurements without some form of calibration. Calibration is the process of configuring the parameters of a model such that its predictive accuracy falls within an acceptable range. Mathematically, this is an optimisation problem. In this chapter, we briefly discuss the calibration problem and the related problem of model uncertainty as it relates to vegetation in the floodplains.

2.3.1 Calibration of the friction factor

In the last century, the complexity of river models has increased such that two-dimensional models with distributed land-use maps are now the standard (more in chapter 3). However, the information in the observations has not increased at the same pace – generally the only continuous measurements are water levels at specific locations. Measurements of discharge are always indirect – extrapolated from flow velocity measurements. River models, like many other environmental models, are therefore ‘overparameterized’, meaning that there are much more parameters than observations (Beven, 2009). This is related to the mathematical problem of underdetermination.

The risk of underdetermination is that there are an infinite number of solutions (combinations of parameter values) that satisfy the required accuracy (in environmental models this is sometimes referred to as 'equifinality', see e.g. Aronica, Hankin, and Beven 1998; Beven 2006). However, this problem is significantly mitigated if some parameters are significantly more sensitive than others – reducing the *effective* number of parameters[9]. In river models, the hydraulic resistance in general and resistance of the main channel particularly are such highly sensitive parameters. Therefore, hydraulic roughness parameters are often directly or indirectly[10] modified such that the model better compares to measurements.

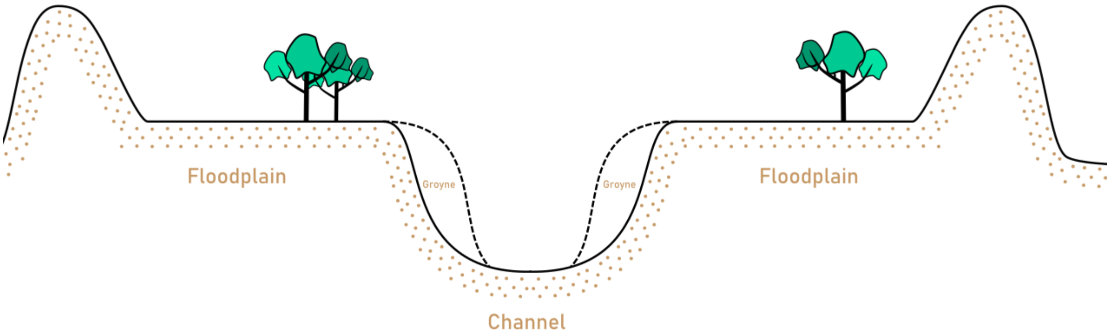

Figure 2.6 A simplified compound channel consist of a single (main) channel and floodplains on one or either side. The (main) channel is generally considered to be restricted to the width between groynes (alternatively: training walls, spur dams, wing dikes, longitudinal training walls). The dimensions of the case (Mosselman & van Velzen, 2011; Querner & Makaske, 2011) *are based on the IJssel river: channel with of 96 m, floodplain width of 700 metre, slope of 0.0835 10^{-3} and main channel depth relative to the floodplain base level of 6.1 m.*

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[9] An important side-note is that sensitivity is not universal but depends on the application. For example: floodplain roughness is not sensitive to water levels at low discharges with no or little flow through the floodplains. At higher discharges, or if the model is used to determine the effect of interventions in the floodplain, it may be a critical parameter.

[10] Direct calibration of the roughness factor involves calibrating Manning’s n or Nikuradse k_s. Indirect calibration may involve a calibration parameter that modifies the result of a roughness formula.

The concept of calibration of roughness parameters seemingly conflicts with the use and development of physical formulas for vegetation (section 2.2.3). However, in (Dutch) practice the main channel roughness is calibrated while the vegetation roughness is fully determined by vegetation resistance equations. However, the two are related. This is illustrated using the case from (Mosselman & van Velzen, 2011; Querner & Makaske, 2011).

Querner and Makaske (2011) argued that one of the assumptions of the vegetation formula of Klopstra et al. (1997) is too conservative. In their opinion, the look-up parameter k_n was calibrated on conditions that did not only include vegetation resistance, but also other sources of energy loss like flow separation at hedges. They computed that a more realistic value and a compound-channel case (Figure 2.6) would lead to a decrease in projected water level of almost 25 cm, which is significant in Dutch practice (Mosselman, 2018a). Mosselman and van Velzen (2011) argued that even if k_n was too conservative, the effect would be less if the main channel roughness would be calibrated to account for this change in floodplain roughness. This case is reproduced in Figure 2.7.

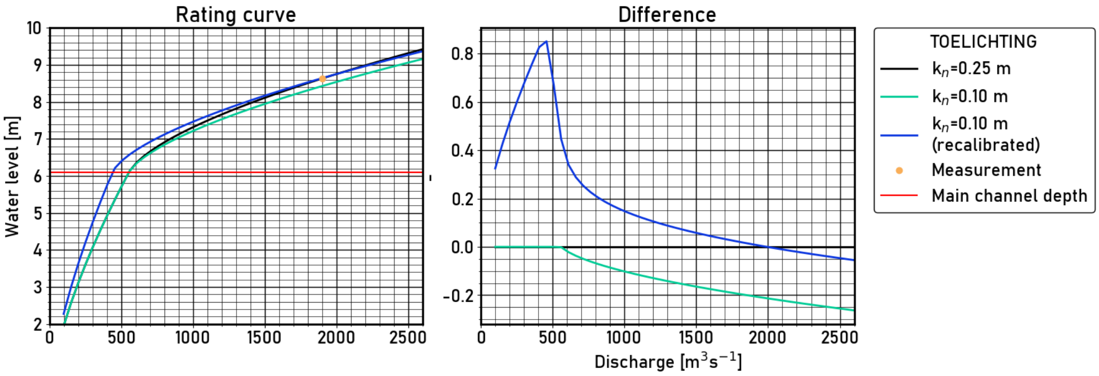

Figure 2.7 An expanded reproduction of the case discussed in (Mosselman & van Velzen, 2011; Querner & Makaske, 2011). The green line follows the reduced floodplain roughness of Querner & Makaske, while the blue line is the case by Mosselman & van Velzen which is recalibrated on the shown measurement. The left figure shows the rating curve (stage-discharge relationship; Q(h) relationship) for a compound channel with the dimensions of Figure 2.6. The right figure shows the difference in water level for both cases compared to the reference case of k_n = 0.25 m. For more details we refer to (Mosselman & van Velzen, 2011).

What this example illustrates is that the calibration is *conditional* on the assumptions and conditions during calibration, and that a change in the assumptions may affect the calibration. Correlation between estimated roughness in vegetated and unvegetated sections of a channel (i.e. not being able to strictly separate the two by calibration) is present at patch scale as well, see Berends et al. 2020).

The analysis of Figure 2.7, while valid, is simplified. It does not discuss validation[11], and it ignores model uncertainty. These topics are further discussed in section 4.6.

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[11] We should note that Mosselman and van Velzen (2011) do mention ‘the model behaves better with a rougher setting for the floodplain’, but validation was not in the scope of that study.

3 Operational state-of-the-art

In this chapter we review the state-of-the-art in practical applications as it is written in various publicly available guidelines in The Netherlands and other nations.

3.1 Rijkswaterstaat

3.1.1 Model management and applications

Rijkswaterstaat maintains a coherent set of models that are used to support policy and operational management. These models are publicly available through the “Informatiepunt Leefomgeving”[12]. All models are created using a standardized procedure (Minns et al., 2022) and for specific applications including water management, navigation, policy support, research and maintenance (van den Hoek et al., 2021). A specific guideline for using models to assess human interventions in rivers is the “*Rivierkundig beoordelingskader”* (Assessment framework for interventions in large rivers) (Doornekamp, 2019).

Within the scope of this report we will focus on the models that are designed for the application of policy and management support and intervention assessment. At the time of writing, these models are still two-dimensional WAQUA[13] models but in the process of being phased out for (two-dimensional) D-HYDRO[13] models.

3.1.2 Ecotope mapping

The vegetation (and roughness) description applied in the Rijkswaterstaat models is based on the ecotope system[14]. An ecotope is defined as an approximately homogeneous ecomorphological, mappable landscape unit. The ecotope system is classified manually based on stereoscopic imagery, and considering water level & depth, flow rate, inundation frequency, salinity and sediment composition (Figure 3.1). This mapping is updated every 4-5 years.

The roughness in the floodplain of the 2D and 3D hydrodynamic models of Rijkswaterstaat is based on the formulations as described in the guideline “Stromingsweerstand vegetatie in uiterwaarden” (van Velzen et al., 2003b, 2003a). This guideline describes more than 30 ‘vegetation structure types’ and combinations of types. This not only involves vegetation patches, but also line vegetation (‘hedges’) and point vegetation (individual ‘trees’). In WAQUA and D-Flow FM these formulations are defined in ‘roughness definition’ files.

3.1.3 From ecotopes to trachytopes

In both WAQUA as Delft3D, roughness is defined using *trachytopes*[15]. Trachytopes determine on a cell-by-cell basis how flow resistance is resolved, e.g. using a constant Manning or a vegetation formula with a predetermined set of parameters. Cells with the same trachytope number use the same equation and parameter values to resolve roughness.

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[12] Previously “Helpdesk Water”: https://iplo.nl/thema/water/applicaties-modellen/modelschematisaties

[13] WAQUA is part of the SIMONA software suit. This software suite was developed to support policy and maintained by Deltares. D-HYDRO is the successor of SIMONA. Internationally, D-HYDRO is known as the Delft3D Flexible Mesh suite. Within D-HYDRO, D-Flow Flexible Mesh (internationally: Delft3D FM) is the successor of WAQUA.

[14] See https://waterinfo-extra.rws.nl/monitoring/biologie/ecotopen/ for more information and interactive maps.

[15] The name comes from ancient Greek τραχύς (“rough”) and τόπος (place, region)

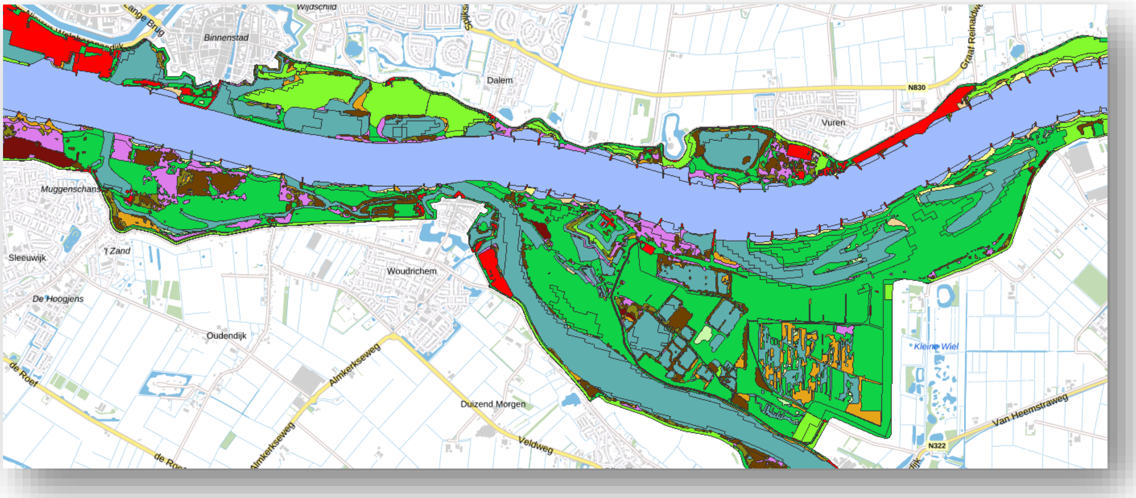

Figure 3.1 Screenshot of the ecotope map viewer of Rijkswaterstaat. This region shows the cities of Gorinchem and Woudrichem. The right-hand side of the map shows the mediaeval castle Loevesteijn and the Room for the River project Munnikenland. The colours show various ecotopes, such as grassland, pioneer vegetation and woods.

There is no one-on-one mapping from the ecotope classification to trachytopes. Instead, mapping tables are available in the Baseline[16] ArcGIS plugin, which takes into account other geo-information as well. The outcome is grid-independent polygons, lines and points with roughness codes, which are stored in the geodatabase. The conversion to model-specific input is also done using this plugin, which projects geodata on a numerical grid (Figure 3.1). This is done based on the weighted area of available roughness values in the Perot areas of the flow links. The result is a trachytopes (**.arl*) file, which contains for each flow link the percentages of the applicable roughness codes from polygon, point ('trees') and line ('hedges') information.

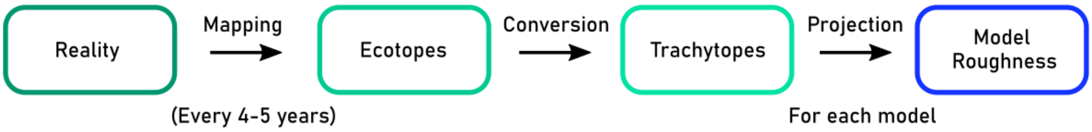

Figure 3.2 An overview of the workflow to get from reality to model roughness (pertaining to vegetation only).

The available ecotope mappings, their resolution and their application in different models is shown in Table 3.1. From 2004, ecotope maps are updated every 4-5 years. These updates of the ecotope maps have a large impact on hydrodynamic models (Berends et al. 2021), usually require a recalibration. From 2012 onward, the resolution of ecotope maps has increased from 20 m to 5 m. This increase in resolution required a recalibration (De Jong, 2015; Spruyt, 2015).

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[16] Baseline is a protocol for storing and manipulating geospatial data to support policy and build models in an automatic and transparent manner. An ArcGIS plugin of the same name is used to interface with the database and convert geospatial data to model input.

Table 3.1 An overview of available ecotope maps, their resolution, and their use in WAQUA and D-HYDRO models. Hydrodynamic models are named as follows: [software]-[river]-[year]_[generation]-[version]. For example: dflowfm2d-rijn-j19_6-v1 is the first version of a sixth-generation model of the Rhine in the D-HYDRO software, modelling the year 2019. In the table below the names are abbreviated to only show the relevant information.

Ecotope mapping	Resolution (m^2)	WAQUA (4th-5th generation models)	D-HYDRO (6th generation models)
1996/1997 (1st revised cycle)	20x20	j93, j95	j93, j95
2004/2005	20x20	j03	-
2008 (2nd revised cycle)	20x20	from j11	-
2012 (3rd cycle)	5x5	from j15_5-v2	from j10/j11
2017 (4th cycle)	5x5	from j19_5-v1	from j19_6
2022/2023 (future cycle)	5x5	-	-

The above workflow is used for models that decribe a specific year (‘current models’; Dutch: *actuele modellen*). Models that are used for permits (policy / B&O *Beheer & onderhoud* models) use a different ecotope map called the ‘legal vegetation map’ (Dutch: *vegetatielegger*). This ‘legal vegetation map’ describes what vegetation is legally allowed to grow where, in order to meet the criteria of specific permits (e.g. flood safety requirements). One of the tasks of Rijkswaterstaat is to ensure vegetation is maintained in accordance with this legal vegetation map. The first legal vegetation map is from 2014, and it was updated in 2020 and 2022.

3.1.4 Resolving trachytope roughness in hydrodynamic modelling

Vegetation roughness is resolved using the formula of Klopstra et al. (1997), as modified by van Velzen et al. (2003a). This formula reads as follows for submerged flow:

$$C = h^{-\frac{3}{2}}(T_1 + T_2 + T_3)$$

with total Chézy roughness C and water depth h. The terms T_1, T_2, T_3 depend on hydrodynamic variables and vegetation parameters. They are fully described in the appendix. For emergent flow (water depths lower than the canopy height):

$$C = \sqrt{\frac{C_d m D h_v}{2g} + C_b^{-2}}^{\,-1}$$

The vegetation parameters $C_d m D h_v$ are the same as those used in the Baptist formula (section 2.2.3). Bed roughness C_b is resolved through the White-Colebrook formula.

In both WAQUA and D-HYDRO, the trachytope roughness field allows for a subgrid approach in two ways: resolving point and line elements and dealing with fractional areas. Point and linear roughness values in a flow link are summed by the inverse of the squared Chézy values. The projection from trachytopes to model-specific input (Figure 3.2) can result in fractional application of resistance formulas, e.g. where one fraction of a cell is assigned to trachytope number 1245, and the other to 1890. In such cases, the lumped roughness in each flow link is determined by weighted (by the surface area fraction) averaging.

The available trachytope classes and their parameter settings are derived from (van Velzen et al., 2003b) and encoded in the assessment framework for interventions in large rivers (Doornekamp, 2019).

3.1.5 Intervention modelling

The *Rivierkundig Beoordelingskader* (Assessment framework for interventions in large rivers) (Doornekamp, 2019) is the official guideline on how to request a permit for which the Dutch Water Directive (*Waterwet*) is applicable. It prescribes that any initiative that may increase the water level must nullify said increase by compensation works[17]. The effect on water levels is computed by specific hydraulic models, following the guidelines set out in that document. To allow for ‘uncertainty in model simulations’, a simulated increase of up to 1 mm is considered negligible. It should be noted that this does not refer to model uncertainty as commonly understood (see section 4.6). If an intervention involves changing hydraulic roughness, the classes as defined in the legal vegetation map (*vegetatielegger*) must be used. Parameter settings of vegetation classes cannot be changed.

3.2 Vegetation roughness in international guidelines

3.2.1 UK: England and Wales

The Environmental Agency (EA) is a non-departmental public body affiliated with the Department for Environment, Food and Rural affairs of the United Kingdom Government. They operate in the UK constituent countries of England and Wales. The EA is among other tasks responsible for conservation and ecology and risk of flooding from main rivers. In that sense, they are comparable to Rijkswaterstaat.

The EA is required to produce evidence on flood risk for development and planning, flood alleviation scheme proposals, flood incident management and emergency planning. Hydraulic models are of ‘particular importance’ in producing this evidence. To help appreciate the quality of these models, the EA published the “Fluvial Modelling Standards” (FMS), published as report LIT 56326 version 4, July 2022 (Haseldine et al., 2022).

Regarding modelling flow resistance, the FMS mention that “*Manning’s n is the roughness coefficient typically used in the UK*” and refers to the Fluvial Design Guide (FDG) on how to estimate the Manning coefficient. The FMS do note that vegetation affects the roughness, leading to seasonal variations (due to vegetation growth and mortality) and the impact of maintenance that removes vegetation. The FMS advise to consider conditions during a flood event in models[18].

The FMS and FDG (Veatch, 2009) recommend look-up tables like those of Chow (1959) to decide which value for the Manning coefficient to use. They also recommend using the CES Roughness Advisor Tool, which is an interactive version of a similar look-up table (Figure 3.3). For 2D roughness a similar approach is recommended – choosing Manning’s *n* values based on land use maps and look-up tables.

3.2.2 UK: Scotland

The Scottish Environment Protection Agency (SEPA) is a non-departmental public body supported by the Scottish Government. It is responsible for flood forecasting, flood warning and flood risk management. SEPA published the Flood Modelling Guidance (FMG, Scottish Environment Protection Agency 2016), which aims to provide a consistent framework to guide model development. According to SEPA, models are ‘key tools in assessing, testing and informing the delivery of flood risk management actions’.

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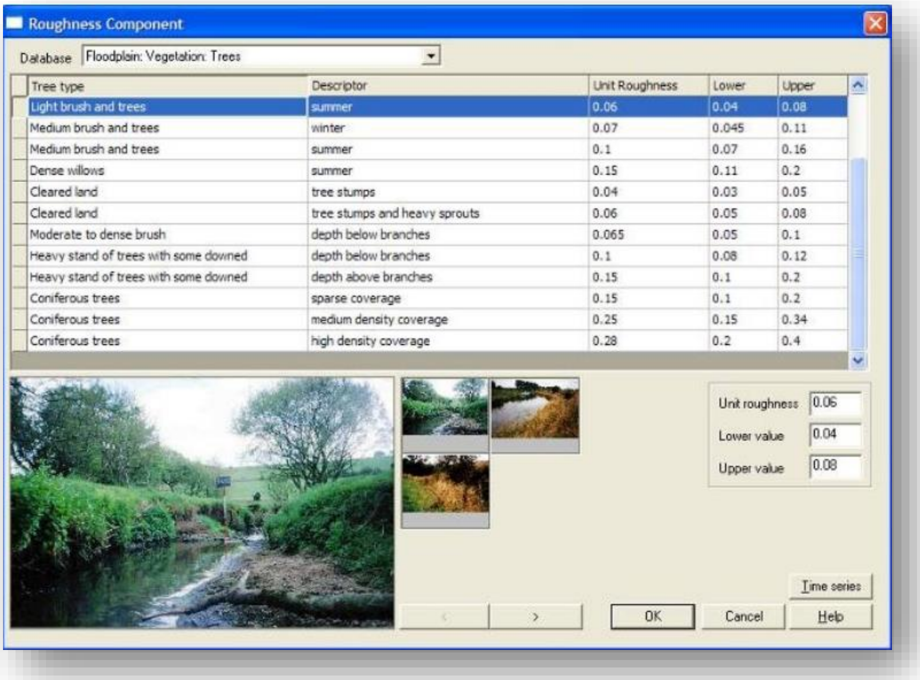
[17] This is law, specifically *Waterbesluit, article 6.15*.

[18] Modelling for flood events only was also Dutch practice, but starting with the fifth generation models in 2012 this focus has shifted to include more conditions (Becker, 2012).

The FMG states that the most common form of roughness “is in the form of Manning’s coefficient (n)”. Vegetation is mentioned as one of the factors that affect the value of *n*. The FMG refers to (Chow, 1959) and the CES Roughness Advisor Tool (see previous section) as methods to determine appropriate values for *n*. They note that any chosen values should be “reasonable and defensible and able to withstand independent review”, and that sensitivity analysis should be carried out. For 2D models specifically, the FMG refers to a system called “OS Mastermap” (presumably comparable to the Dutch Baseline system) which contains land cover layers. Different roughness values are to be assigned to each land cover class.



Database: Floodplain: Vegetation: Trees

Tree type	Descriptor	Unit Roughness	Lower	Upper
Light brush and trees	summer	0.06	0.04	0.08
Medium brush and trees	winter	0.07	0.045	0.11
Medium brush and trees	summer	0.1	0.07	0.16
Dense willows	summer	0.15	0.11	0.2
Cleared land	tree stumps	0.04	0.03	0.05
Cleared land	tree stumps and heavy sprouts	0.06	0.05	0.08
Moderate to dense brush	depth below branches	0.065	0.05	0.1
Heavy stand of trees with some downed	depth below branches	0.1	0.08	0.12
Heavy stand of trees with some downed	depth above branches	0.15	0.1	0.2
Coniferous trees	sparse coverage	0.15	0.1	0.2
Coniferous trees	medium density coverage	0.25	0.15	0.34
Coniferous trees	high density coverage	0.28	0.2	0.4

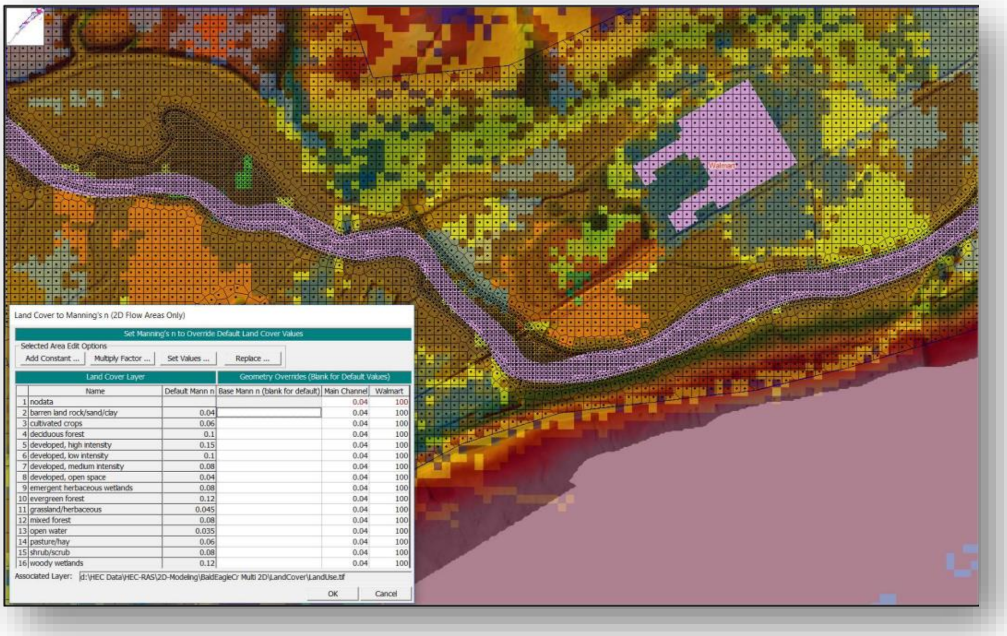
Unit roughness: 0.06
Lower value: 0.04
Upper value: 0.08

Figure 3.3 Screenshot of the CES Roughness Advisor Tool (Veatch, 2009)

3.2.3 United States

The Unites States Army Corps of Engineers Institute for Water Resources (USACE-IWR) was established to provide forward-looking analysis and tools to aid the Civil Works Program of the USACE. These civil works include flood protection and ecosystem restoration. One of the centres of the USACE-IWR is the Hydrologic Engineering Center (HEC). It published Technical Directive 41, entitled “Modeler Application Guidance for Steady vs Unsteady, and 1D vs 2D vs 3D Hydraulic modelling” (Brunner et al., 2020). This document TD-41 aims to provide entry- to mid-level hydraulic engineers with guidance on flow modelling.

TD-41 notes that for 2D and 3D modelling the modeller is required to lay out spatial vegetation information and relate that to roughness values. This is done by relating them to Manning’s *n* values (Figure 3.4). Spatial vegetation information can be obtained from aerial photography (p. 6-22), but no mention is made of any centralized database of land-cover maps. TD-41 notes that the calibration process is generally much more difficult for 2D, as it requires the user to decide over what spatial extent to change the roughness.



Land Cover to Manning's n (2D Flow Areas Only)

Set Manning's n to Override Default Land Cover Values

Selected Area Edit Options

Land Cover Layer			Geometry Overrides (Blank for Default Values)		
	Name	Default Mann n	Base Mann n (blank for default)	Main Channel	Walmart
1	nodata			0.04	100
2	barren land rock/sand/clay	0.04		0.04	100
3	cultivated crops	0.06		0.04	100
4	deciduous forest	0.1		0.04	100
5	developed, high intensity	0.15		0.04	100
6	developed, low intensity	0.1		0.04	100
7	developed, medium intensity	0.08		0.04	100
8	developed, open space	0.04		0.04	100
9	emergent herbaceous wetlands	0.08		0.04	100
10	evergreen forest	0.12		0.04	100
11	grassland/herbaceous	0.045		0.04	100
12	mixed forest	0.08		0.04	100
13	open water	0.035		0.04	100
14	pasture/hay	0.06		0.04	100
15	shrub/scrub	0.08		0.04	100
16	woody wetlands	0.12		0.04	100

Associated Layer: d:\HEC Data\HEC-RAS\2D-Modeling\BaldEagleCr Multi 2D\LandCover\LandUse.tif

Figure 3.4 Examples of land use and user defined polygons to define roughness for a 2D model, from (Brunner et al., 2020). Note that the window on the left is titled 'Land cover to Manning's n (2D Flow Areas Only).

3.2.4 Germany

The *Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall* (DWA) is an independent organization that is regarded as a rule-setter and educational institute in Germany. DWA publishes guidelines (*Merkblatts*) that contain technical guidance to engineers. Merkblatt DWA-M 524 "*Hydraulische Berechnung von Fließgewässern mit Vegetation*" (Hydraulic computation of vegetated rivers) describes how to resolve vegetation roughness in models. For 2D flow models, DWA-M 524 provides a guide (Table 9, p. 76) to choose an equation to resolve flow resistance, depending on the type of vegetation (Table 3.2). Anthropogenic and natural variability of vegetation in time and space is described, but no specific method is recommended for dealing with this.

Table 3.2 Recommended vegetation resistance formulas following DWA-M 524 (Wasserwirtschaft & Abwasser und Abfall e. V. (DWA), 2020). The formulas can be found in Appendix A. Note that DWA-M 524 expresses all formulas in the Darcy-Weisbach coefficient. In this report, we express all in Chézy. The conversion between the two is relatively straightforward and can be found in equation (4).

	Rigid	**Flexible**
Emergent	(Pasche, 1984; Pasche & Rouvé, 1985)	(Järvelä, 2004; Västilä & Järvelä, 2017)
Submerged	(Huthoff et al., 2007) and (Pasche, 1984)	(Huthoff et al., 2007) and (Västilä & Järvelä, 2017)

3.2.5 Australia

Engineers Australia is a non-profit, independent professional society. It publishes influential guidelines, particularly the Australian Rainfall and Runoff series which was first published in 1958. The latest version was published in 2019 (Ball et al., 2019). It aims to describe the industry best practice, to improve design practice, management and policy and planning decisions. Here we refer to Book 6 of this series on flood hydraulics.

Regarding hydraulic roughness, the Manning coefficient is considered a popular international formula and the most used approach in Australia. The guideline refers to (Chow, 1959) for choosing 1D values for the Manning coefficient. Roughness in 2D models is “generally specified as a map and based on land-use information that can be derived from aerial photography, satellite images, planning zone maps or field observations”. It is mentioned that LiDAR techniques exist but are not a commonly adopted technique. The parametrization of roughness from land-cover maps is commonly done through the Manning formula as well. The handbook provides a look-up table, ranging from values of 0.03 $s.m^{-1/3}$ to 0.12 $s.m^{-1/3}$ in the floodplains depending on the density of the vegetation. Three classes are distinguished: grasses or minimal vegetation (0.03-0.05 $s.m^{-1/3}$), shrubs or moderate vegetation (0.05-0.07 $s.m^{-1/3}$) and trees or thick vegetation (0.07-0.12 $s.m^{-1/3}$). Please note that vegetation is mentioned specifically as a potential source of channel blockage due to uprooting and debris flow.

4 Trends in vegetation research

In this chapter we identify various scientific developments that are related to modelling vegetation resistance. We briefly discuss the current state of the field in (scientific) literature. If some work has already been done that may put the scientific progress in context for application to the Dutch rivers, we provide this interpretation in a text box.

4.1 Remote sensing of vegetation

Remote sensing is commonly used in environmental sciences and forestry for vegetation mapping and inventory. Remote sensing (RS) is an umbrella term indicating an ensemble of several techniques which differs in their functioning and products.

The different kinds of instrumentation used by each technique can be mounted over various platforms (e.g. tripod, vehicle, unmanned aerial vehicle (UAV), aircraft, satellite). The choice of a sensor, or a combination of more sensors and techniques, and the platform is usually related to the needed information, the desired area coverage and spatial resolution, and the available budget. In this way, RS provides solutions that can be customised according to the specific features of the area and target to survey.

4.1.1 Vegetation mapping

RS techniques for vegetation mapping generally involve passive sensors. Passive sensors record the electromagnetic energy signal reflected or emitted by a surface and distinguish among different surfaces based on their spectral signature[19].

Aerial photography, obtained through optical sensors, represents the cheapest way for land cover classification by providing RGB images (i.e. coloured images given by the combination of red, green and blue spectral bands). However, RGB-based mapping has various drawbacks because to the limited number of spectral bands. RGB-based mapping might therefore misclassify vegetation as turbid waters or dark sediments and vice versa. Consequently, multispectral or hyperspectral imagery is usually the preferred technique for land cover classification despite the higher cost of their sensors (Gómez et al., 2016).

Multispectral images are composed of 4 to 10 spectral bands covering the electromagnetic spectrum from blue to infrared wavelengths, while hyperspectral images span over the same range but with finer spectral resolution (100-1000 spectral bands). The additional information provided by multi- and hyperspectral imagery with respect to RGB is crucial for vegetation detection. In particular, the near-infrared band allows discriminating plants from other elements as the spectral signature of vegetation shows a peak of reflectance for near-infrared, unlike other land cover classes (Thenkabail & Lyon, 2016).

For practical use in the Dutch floodplains, Deltares does not recommend hyperspectral imagery because of the excessive associated costs and limited additional value with respect to multispectral solutions. In contrast to hyperspectral imagery, multispectral images are available from satellite images. Satellite imagery is more affordable, user-friendly and available on the scale required for large-scale river modelling.

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[19] The spectral signature of an object is its characteristic pattern of reflection and absorption of the electromagnetic signal at different wavelengths

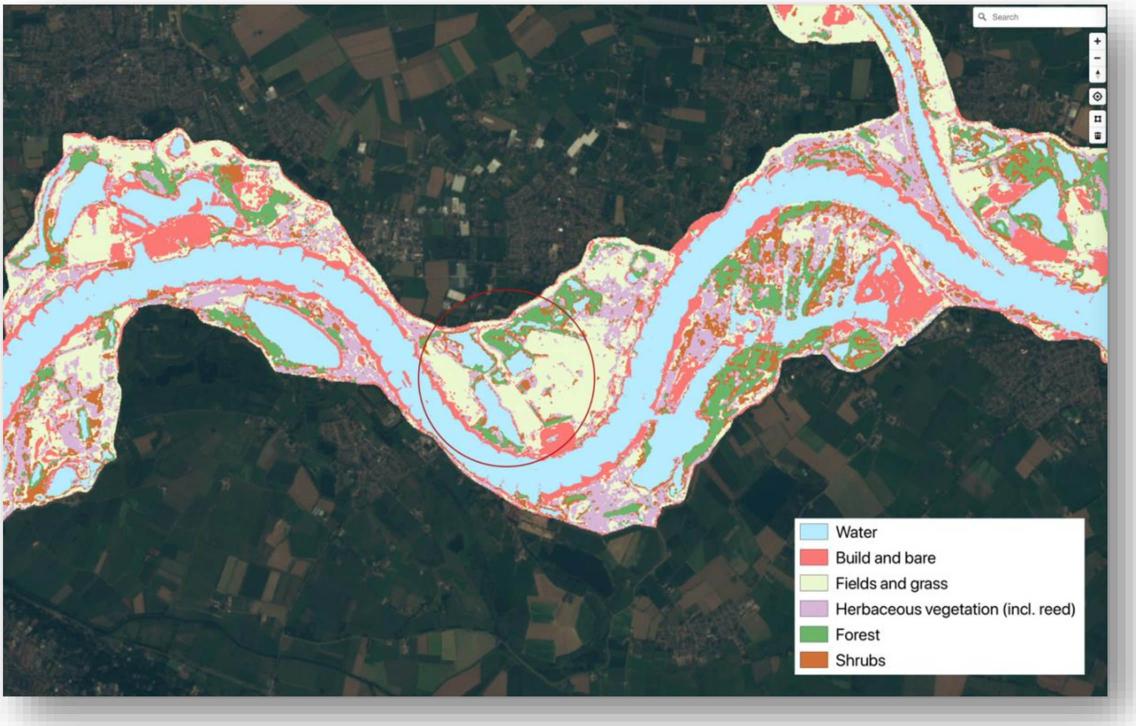

Figure 4.1 Example classification result of a single date on the fly classification (26-8-2019), from (Geerling et al., 2021)

Vegetation mapping in practice
Rijkswaterstaat uses the *vegetation monitor* web-app for its daily management of the floodplains. In this application Sentinel2 images are combined with data from the AHN3 digital elevation map of the Netherlands and classified using Random Forest algorithms, taking the most recent ecotope map as a test and training dataset. Both daily image classification and annually averaged images are made available.

Classifications are compared with the legal vegetation map (*vegetatielegger*, see section 3.1.3) to screen for hotspots where vegetation produces more flow resistance than allowed according to this map. Based on this screening assessment priority areas are identified that require field visits to assess the true status in the field together with local stakeholders (Geerling et al. 2021).

URL: https://vegetatiemonitor.rijkswaterstaat.nl

4.1.2 Vegetation survey

In addition to mapping, some remote sensing techniques can support vegetation inventory to measure vegetation health, status and biomass through the computation of spectral indices (Ceccato et al., 2001; Mitchell et al., 2015; Pettorelli et al., 2005). The most common of these indices is the Normalised Difference Vegetation Index (NDVI), a function of the red and near-infrared spectral bands. The NDVI is commonly accepted as a proxy of vegetation biomass for some plant species, but it can saturate in very densely vegetated forests (Pettorelli et al., 2005). For this reason, other remote sensing techniques and sensors might be preferred for vegetation inventory.

For instance, photogrammetry provides three-dimensional point clouds representing the canopy surface (i.e. the Canopy Height Model, CHM). Several methods have been developed to measure vegetation height and perform individual tree detection (ITD or individual crown detection ITC) based on the CHM (Iglhaut et al., 2019; Lindberg & Holmgren, 2017; van Iersel et al., 2018). Coupling ITD/ITC methods with allometric[20] information is possible to provide a detailed description of the shadow-intolerant plants the crown of which constitute the upper canopy layer. However, this approach has a limited range of applications in terms of forest type since it disregards understory and shadow-tolerant plants.

The vertical description of plant structure is provided by active sensors, such as Light Detection And Ranging (LiDAR). LiDAR generates a three-dimensional point cloud representing the surfaces that have reflected the signal emitted by the LiDAR sensor. The LiDAR signal can have different wavelengths able to penetrate different surfaces. The most common (and cheapest) sensors are called *red LiDAR* and can pass through vegetation but not through water. The more expensive *green LiDAR* can penetrate vegetation and water. Although many works still apply CHM-based methods to retrieve vegetation information, more recent methodologies leverage the full information provided by LiDAR sensors. For a review of methods for airborne lasers scanner, refer to (Lindberg and Holmgren 2017; Latella, Sola, and Camporeale 2021), while for vegetation inventory based on terrestrial laser scanner refer to (Calders et al., 2020; Dassot et al., 2011; Liang et al., 2016).

Generally, the use of red LiDAR in riparian applications has consistently increased since the 2000s (Bailly et al., 2012; Huylenbroeck et al., 2020) for local (Cartisano et al. 2013; Latella et al. 2020; 2022) up to regional studies (Michez et al., 2017), together with the use of multi- and hyperspectral imagery (Huylenbroeck et al., 2020).

Photogrammetry and LiDAR methods are labour-intensive, especially on the scale of floodplain management for Rijkswaterstaat. However, they have important practical benefits. For example, the classification of the *vegetatiemonitor* (vegetation monitor web-app; Geerling et al. 2021) has -benefited from (red) LiDAR data, available from the national digital elevation model (DEM) campaigns (AHN; *Algemeen Hoogtemodel Nederland*), to distinguish willow shrubs from willow forests based on their height (considering that their spectral signal is similar). Moreover, this data once collected can be used for many purposes. This underlines the benefit of collective or publicly published measurement campaign, such as AHN.

Green LiDAR is not considered a viable option for Dutch inland water systems. Dutch waters tend to be turbid with dark sediments at the bed, which results in high signal absorption and unreliable results (Penning & Visser, 2019).

4.1.3 Considerations in the use of Remote Sensing Data

The use of remote sensing for vegetation mapping and inventory can reduce the number of field surveys necessary to characterise a vegetated area and provide spatially continuous features over larger domains, potentially in a multitemporal way (Carbonneau & Piégay, 2012; Piégay et al., 2020; Tomsett & Leyland, 2019). Additionally, remote sensing through satellites provides nearly daily images of large-scale areas, facilitating a much more ‘up-to-date’ view of the current status for such large spatial extents than comparable data retrieved from field visits. Nevertheless, some crucial factors must be considered.

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[20] In forestry, allometry refers to relationships between the size of a body part and the size of the whole body or another part.

1 **Need for field measurements**
Although remote sensing allows the implementation of automated analysis over extended domains, it requires some ground truth and field measurements to train classification algorithms, calibrate allometric[20] relationships and validate the results (e.g. classified vegetation maps).

2 **Need for homogeneous conditions**
Remote sensing acquisitions must be adequately designed by considering external (lighting, atmospheric conditions) and physiological (e.g., plant life-cycle phase) factors. For instance, Belcore and Latella (2022) noticed that at least two surveys in different phenological phases were necessary to improve individual tree detection based on photogrammetric data. Also, Azzari and Lobell (2017) investigated the influence of phenological variability on multispectral-based land cover mapping indicating how to achieve higher classification accuracy. One solution, especially for relatively low-dynamic systems, is to average images over a longer period.

3 **Limited literature on submerged vegetation**
Finally, remote sensing has been mostly applied to (emergent) terrestrial vegetation. Despite rising interest in submerged vegetation mapping with green LiDAR and multi- or hyperspectral imagery (Silva et al., 2008), this kind of application still requires to be fully explored.

Submerged vegetation is less relevant for the Dutch floodplains; however, a pilot study was performed in 2018 for Rijkswaterstaat using drone, airplane and satellite-based imagery for the shallow Eem and Gooi lakes. Here it was demonstrated that remote sensing of aquatic (submerged) vegetation was not sufficiently reliable for daily practice with currently available techniques and could not replace or be used to limit the current method of field surveys (Penning & Gaytan Aguilar, 2018).

4.1.4 Remote sensing to inform hydraulic modelling

Vegetation monitoring through remote sensing can inform hydraulic models by providing quantitative input about spatial vegetation configuration and features (Shields et al., 2017). In scientific literature, various works have performed floodplain roughness parameterization for hydrodynamic river modelling by using LiDAR data and/or multispectral imagery (van der Sande, de Jong, and de Roo 2003; Straatsma and Baptist 2008; Vetter et al. 2012; Forzieri, Castelli, and Preti 2012; Manners, Schmidt, and Wheaton 2013; Jalonen et al. 2015; Zahidi et al. 2018; Latella et al. 2020).

Riparian vegetation comprises mature trees and flexible plants (i.e. young trees, shrubs, bushes, reeds, herbaceous vegetation and grass), as well as crops (e.g. corn; see van Dongen 2022). Hydraulic models can assimilate mature trees to rigid cylinders and compute the associated flow resistance with literature formulas (see section 2.2.3). An alternative way to derive vegetation density from remote sensing is the Leaf Area Index[21] (LAI; Box, Järvelä, and Västilä 2021; Chaulagain et al. 2022), coupled with species-specific information such as reconfiguration parameters (see section 4.2).

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[21] The Leaf Area Index (LAI) is defined as the one-sided green leaf area per unit of ground surface area.

While RS has great potential to inform hydraulic models, its usability highly depends on its accuracy and detail. For example, the accuracy of RS-derived ecotope maps, , can be expressed in error matrices that compare the classified type to ground-truth (or human-classified) maps. It has been estimated that the uncertainty introduced by inaccurate ecotope maps is a major source of model uncertainty (Straatsma and Huthoff 2011; Straatsma et al. 2013; Warmink, Straatsma, et al. 2013).

In the perspective of uncertainty reduction, the generation of guidelines or standard procedures to support remote-sensing-informed hydraulic modelling can provide a framework to set models based on the same input conditions (e.g. similar amount of supporting data, field surveying conditions, remote sensing data and analysis tools).

4.2 Vegetation reconfiguration

Vegetation reconfiguration refers to the deformation of vegetation by flow. Reconfiguration commonly refers to two different ways of deformation, i.e. streamlining and canopy deflection (Järvelä, 2004; Verschoren et al., 2016). Either or both forms of deformation can be referred to as ‘flexible vegetation’ in literature. Figure 4.2 shows both types of deformation.

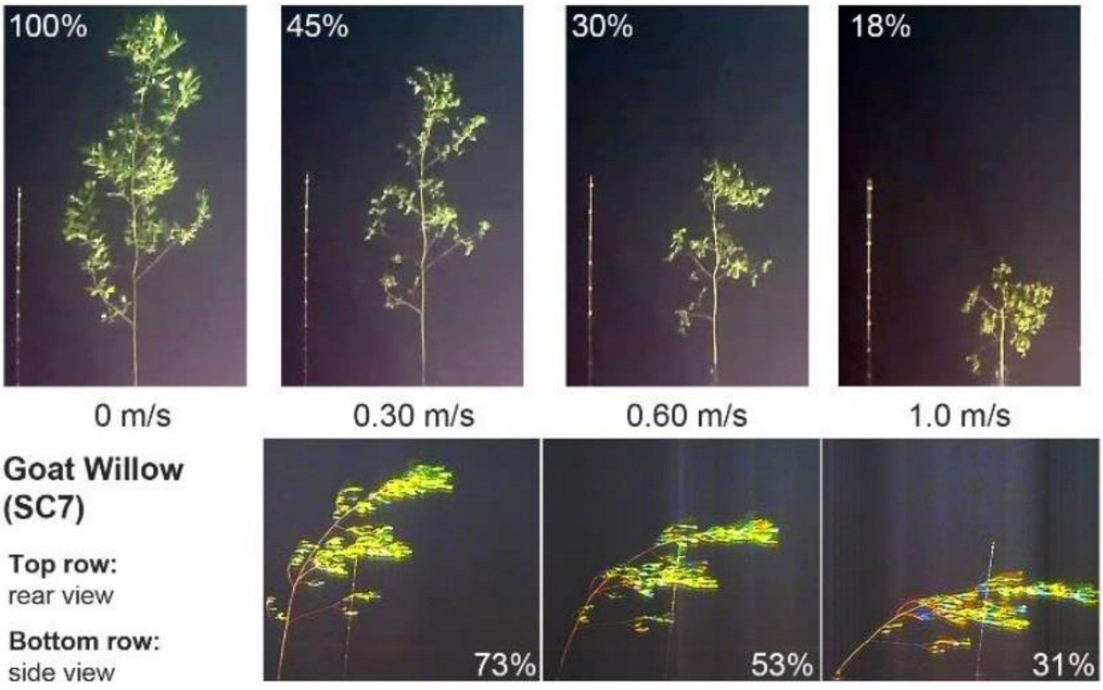

Figure 4.2 Vegetation reconfiguration showing both canopy deflection (reduction of vegetation height) and streamlining (aligning of foliage and branches with the flow) under increasing flow velocity. Percentages in upper row indicate the projected area compared to no-flow case; lower row indicates the same for height. The tree was 1.8m tall. Photo’s credited to Juha Järvelä of Aalto University.

4.2.1 Vegetation streamlining

Streamlining of vegetation refers to the deformation of the vegetation to reduce drag. The relationship between drag reduction and flow velocity was expressed by Vogel (1989) as

$$F \propto \bar{u}^{\chi} \tag{9}$$

with force F, depth-averaged flow velocity $\bar{u}$ and Vogel exponent χ. Although this relationship has as downside that it is dimensionally inconsistent in the form of (9) , it has been experimentally demonstrated and has found application in the equations of Järvelä (2004a) and Västilä and Järvelä (2014) (which are dimensionally consistent), see Appendix A.4 for a description of the experimental implementation in Delft3D. The Järvelä (2004a) formula can be expressed in terms of the dimensionless vegetation density term ϕ [-] as:

$$\phi = C_{D,\chi}\mathcal{L}\left(\frac{u_c}{u_\chi}\right)^{\chi} \tag{10}$$

with velocity through the vegetation layer u_c [m.s^{-1}], leaf-area index $\mathcal{L}$ [-], scaling parameter u_χ [m.s^{-1}], species-specific drag coefficient $C_{D,\chi}$ [-] and Vogel exponent χ [-]. The formula by Västilä and Järvelä (2014) is similar to (10), but with an added term for foliage, which can be used to make a distinction between winter (without foliage) and summer (foliated) conditions. Look-up tables for $C_{D,\chi}$,χ are based on lab experiments, e.g. see Table 4.1.

It should be noted that for relatively low flow through unfoliated vegetation – as might be the case for most conditions in the Dutch floodplains – the term $\left(\frac{u_c}{u_\chi}\right)^{\chi}$ will approach one for most species. In that case, the Järvelä (2004a) formula as implemented in Delft3D reduces to the Baptist equation provided that the Leaf Area Index is comparable to the blockage area ($\mathcal{L} \sim mDh_v$). The extent to which this is true, as well as the relative effect of foliage, remains to be tested.

Table 4.1 Parameter values for various species for stem (subscript S) and foliage (subscript F), to be used in the formula by Västilä and Järvelä (2014). This table is an excerpt from that publication.

Species	$C_{D,\chi,F}$	χ_F	$C_{D,\chi,S}$	χ_S
Alnus glutinosa **(common alder)**	0.18	-1.11	0.89	-0.27
Salix Caprea (goat willow)	0.09	-1.09	0.82	-0.25
Species-averaged	0.14	-1.11	0.93	-0.26

4.2.2 Deflection of the vegetation canopy

Early Dutch research on flexible vegetation for the Dutch case was carried out by Klaassen et al. (1999), based on experimental research on reeds by HKV. They estimated the effect of canopy deflection and concluded that flexibility of reeds (they used the more general Dutch term *moerasvegetatie*) has a negligible effect on overall roughness. Querner and Makaske (2011) adopted this conclusion in their general critique on the representation of floodplain vegetation in flood models. However, Klaassen et al. (1999) remark that while their calculations show deflection leads to a negligible [$\mathcal{O}(1\ \mathrm{cm})$] effect on water levels for reeds, it may have more effect for grasses or other vegetation types that were not studied. They argue to develop a universal roughness estimator for flexible vegetation.

However, lab experiments have shown that the drag force on a single plant greatly depends on flexibility, amongst other things (Blamauer et al., 2011; Freeman et al., 2000). One model for plant bending is proposed by (Van de Wiel, 2003), who iteratively computes the bending angle and resulting roughness until the drag force exerted by the flow equals the force needed to bend the plant stem (Blamauer et al., 2011):

$$F_\alpha = \frac{6EI}{h_v^2} \sin^2 \alpha_v \tag{11}$$

where *E* is the modulus of elasticity, *I* the second moment of inertia, and α_v the bending degree. Bending feeds into the common roughness equation through modification of the projected area:

$$A_p = mDh_d \tag{12}$$

where h_d is the deflected canopy height ($h_d = h_v \cos \alpha_v$). Verschoren et al. (2016) used a similar modification of the vegetation height to model submerged aquatic vegetation with Delft3D but based the amount of deflection on field experiments and applied an empirical formula to determine the deflection angle ($\alpha_v \propto \bar{u}$). In their case study Blamauer et al. (2011) found bending angles up to 31°, but noticed that the amount of bending strongly depends on vegetation being emergent or submerged. Box, Järvelä, and Västilä (2022) note that in-situ measurements on the deflection of vegetation remains scarce. They criticize EI approaches for being complex and not considering foliage. Instead, they recommend further testing and improving empirical approaches.

Van Velzen and Jesse (2005) derived the effect of overall reconfiguration (bending and streamlining) from the study of Freeman, Raymeyer, and Copeland (2000). Assuming that *Cornus Sericea* and *Euonymus* were most representative for the shrub species native to the Dutch floodplains, they assumed a combined effect on projected area of 1.2 for trees and 1.5 for all other vegetation relative to winter vegetation.

4.3 Vegetation dynamics

Vegetation dynamics refers to the study and simulation of growth and mortality of vegetation. While it is generally understood that vegetation growth has a profound effect on hydraulic roughness over the course of seasons or years, current best practice recommends accounting for vegetation growth by choosing representative conditions during a flood (per the review of national guidelines in chapter 3.2). In this section, we cover some trends that deal with considering vegetation dynamics explicitly in hydraulic models.

4.3.1 Cyclic rejuvenation

Allowing (limited) vegetation dynamics is favoured from an ecological point of view because of its contribution to biodiversity. In the exploration of a Cyclic Floodplain Rejuvenation approach (CFR; Baptist et al. 2004a; Baptist et al. 2004b) approach in the early 2000s that would combine both flood protection and nature restoration objectives, quantification of biogeomorphological developments was technically difficult due to lack of appropriate tools (numerical models) and process knowledge. Since then, both the biogeomorphological capabilities and the computational efficiency of the tools have increased (van Oorschot et al., 2015), enabling better quantification of biogeomorphological developments and associated flood levels, under different scenarios. These scenarios may include assessing the effect of changing discharge regimes because of climate change, dam management and invasive species.

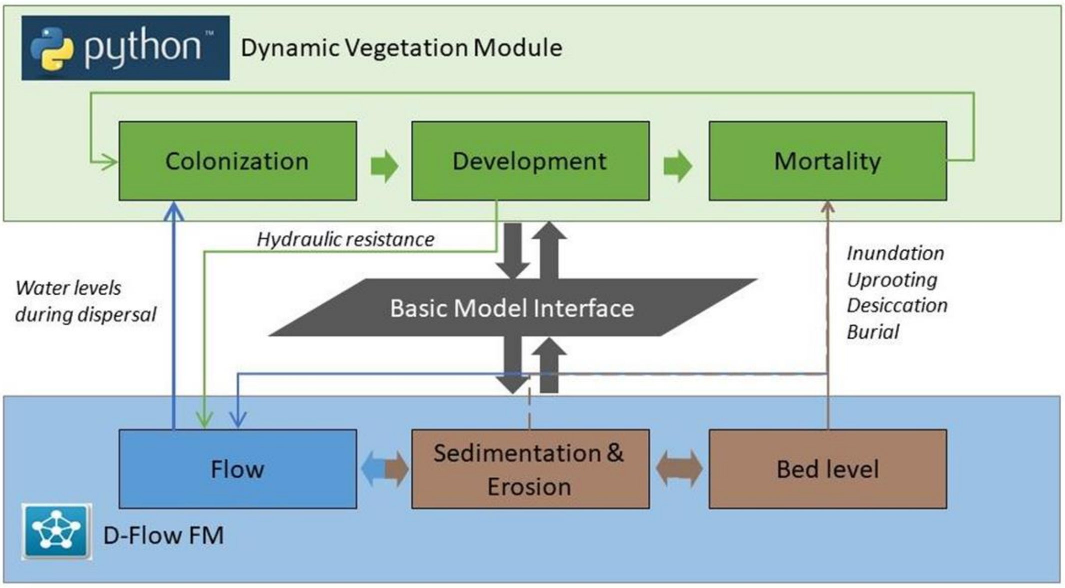

Figure 4.3 Flow diagram of a flexible model setup allowing for full biogeomorphological feedbacks: The ecological model (coded in Python, which is open source and allows for coupling to other models) simulates vegetation development and governs the timing of variable exchange. The D-Flow FM (part of the Delft3D Flexible Mesh suite, which is marketed as D-HYDRO in The Netherlands) model computes hydro- and morphodynamic stresses, which are communicated with the ecological model through memory using the Basic Model Interface technique that saves computational work and makes operations more user friendly and robust than with earlier experimental model setups.

The expected water level increase of cyclical rejuvenation on flood levels were estimated (using 1D SOBEK simulations) at 10 cm over 10 years and 20 cm over 50 years, due to both vegetation dynamics and increased sedimentation – so most of the effect is expected in the first 10 year (Baptist, Smits, et al., 2004). However, in (Dutch) practice it is challenging to predict long-term changes correctly, as human interference including vegetation management tend to be more dominant than natural processes (Harezlak et al., 2020).

4.3.2 Dynamic vegetation models

In literature, various models are proposed to deal with vegetation dynamics. Here we briefly introduce two, namely the RipVeg and CR06 models.

At Deltares, an ecological model (RipVeg, Riparian Vegetation Module) is developed to be part of the NBSDynamics project[22], and which is a further development of the model of van Oorschot et al. (2015). RipVeg calculates plant establishment, growth and dieback based on vegetation type and age, and hydro- and morphodynamic stresses computed by a hydraulic model, over a representative period. The resulting new plant properties are communicated back into the hydraulic model, which calculates new hydrodynamics and bed updates matching the new hydraulic roughness, and so on (see Figure 4.3). Because the coupling interval is flexible, and the ecological model can be adapted easily, multiple issues can be addressed at different scales. For instance, seasonal dynamics of existing vegetation can be addressed at the river reach scale, but these models can also be applied to simulate the development of a new side channel over multiple years. Not all possibly relevant processes have been incorporated yet. Groundwater has been implemented in a simplified manner, by averaging the water level of the nearest three wet cells and linking it to a capillary fringe parameter to simulate mortality due to drought. At the moment, RipVeg supports riparian trees and annual herbs. Perennial species and aquatic vegetation are not supported.

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[22] https://deltares.github.io/NBSDynamics/

A different approach to model vegetation dynamics is CR06 proposed by Camporeale and Ridolfi (2006). CR06 is a stochastic model which computes the probability density function of woody biomass. It assumes negligible inter-species competition and synergy, steady river morphology and instant communication between groundwater level and water level in the river. An application of this method using Delft3D is described by (Latella et al. 2020).

4.3.3 Seasonal vegetation

Seasonality refers to the annually varying signal in hydraulic roughness due to the growth and decay of vegetation over the year. In winter the hydraulic roughness can be assumed to be less than in summer, due to the combined effect of vegetation growth and the presence of foliage in summer.

In the Dutch rivers, summer floods are rare in relation to winter floods. Here, summer floods refer to floods occurring in the months from April to November (van Velzen & Jesse, 2005). In November 1998 there was a flood in the Rhine with a maximum discharge of approximately 9,490 m^3s^{-1}. Measurements of flood levels showed higher water levels than expected based on rating curves. While it was assumed that this was caused by summer vegetation (the rating curves were derived on winter conditions), this was not tested until 2005.

Van Velzen and Jesse (2005) studied the effect of summer vegetation on flood levels for the Dutch Rhine branches by estimating (i) the increase of projected area due to foliage, (ii) the decrease in projected area due to increased reconfiguration and (iii) an increase due to undergrowth. They applied their modified parameter set (using the methodology described in chapter 3.1) to the summer flood of 1998. They concluded that it was likely that summer vegetation caused the higher water levels, although they note considerable uncertainty in the discharge measurements. Extrapolating to design conditions (16,000 m^3s^{-1}), however, they estimated a 12-37 cm increase in water levels compared to winter conditions.

Following the 2021 summer flood on the Meuse, Rijkswaterstaat commissioned Arcadis to develop a method to estimate the effect of summer vegetation (van Dongen, 2022). They concluded based on analysis of aerial photography that there are no significant changes in vegetation type between summer and winter, with the notable exception of crops, but that other parameters (density, height) do change. They recommend additional research to map the differences in vegetation parameters based on maintenance strategy (e.g. mowing and a agriculture). For other vegetation types, they recommend using the existing guidelines, i.e. (van Velzen et al., 2003b, 2003a; van Velzen & Jesse, 2005).

The Dutch studies described above focus on modifying the existing parameters to predict the effect of summer vegetation. However, both studies note that there is little evidence to validate such simulations, or assumptions of the chosen parameter settings.

In literature there are various approaches to measure the seasonality of vegetation. Boothroyd, Nones, and Guerrero (2021) measured the NDVI (see section 4.1) and found a seasonal signal (Figure 4.4) as well as a long-term trend. For smaller channels, various authors found a seasonal signal in hydraulic roughness due to the growth of aquatic vegetation (Errico et al. 2018; Perret, Renard, and Le Coz 2021; Berends et al. 2022).

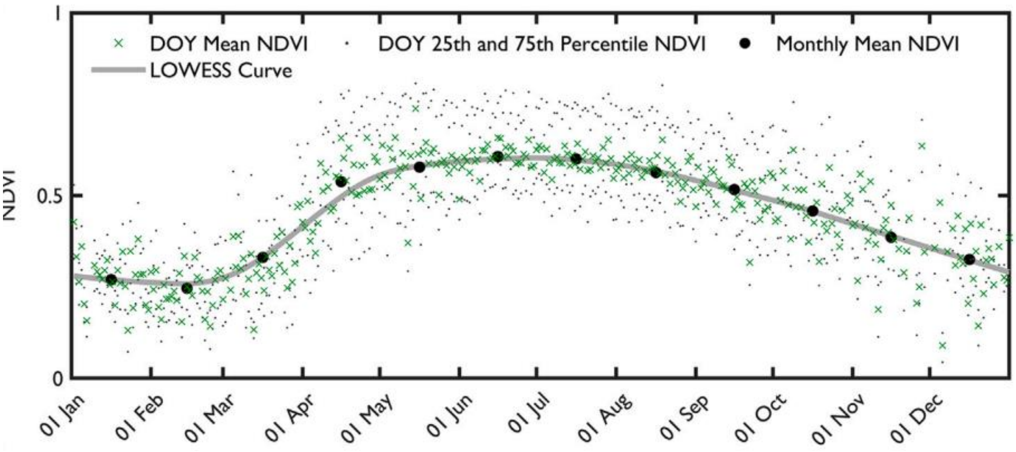

Figure 4.4 Seasonal signal of the NDVI (see section 4.1) within the Po River. From (Boothroyd et al., 2021)

4.4 Uprooting of vegetation and floating debris

Vegetation does not only affect flow by increasing hydraulic roughness. Uprooted vegetation – particularly trees – may be transported as floating debris during floods and cause significant blockages. In the last decades, the source of wood elements, transport of wood and wood-structure interaction has been studied (Innocenti et al., 2022).

4.4.1 Uprooting of vegetation

The uprooting of vegetation refers to the removal of vegetation by flow when the root anchoring force is reduced (e.g. through bed erosion) to equal the drag on the plant (Calvani, Carbonari, and Solari 2022). Once uprooted, vegetation no longer contributes to the increase in flow resistance. Uprooting can be modelled as a function of scour (e.g. see section 4.3 ;van Oorschot et al. 2015). Calvani, Francalanci, and Solari (2019) developed an alternative conceptual model to predict the chance of uprooting based on critical flow velocity or critical Froude numbers. This approach was applied to the Meuse 2021 flood (Calvani et al. 2022), predicting that various regions along the Meuse were susceptible to uprooting. However, these results could not be validated with field data.

4.4.2 Accumulation of woody debris at bridges

Accumulation of woody debris may lead to structural damage at bridges and bridge piers, block flow and increase flood risk. Panici et al. (2020) proposed a practical desk-based analysis to assess which bridges are prone to risk (Figure 4.5). Innocenti et al. (2022) reviewed how large wood elements (LW[23]) have been implemented in national guidelines in the US, Switzerland, Italy and UK. Of these countries, only the UK has implemented a methodology for assessing the risk of woody debris in their national guidelines[24]. However, various procedures are proposed in the other countries. For example, the "Event Dynamics Classification (EDC)" method has been proposed for Italy within the larger IDRAIM framework for integral river management (Rinaldi et al., 2015).

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[23] Large Wood is defined as having a length larger than 1 m and diameter larger than 0.1 m.

[24] United Kingdom (UK) National Highway scour risk assessment (CS 469), Management of scour and other hydraulic actions at highway structures

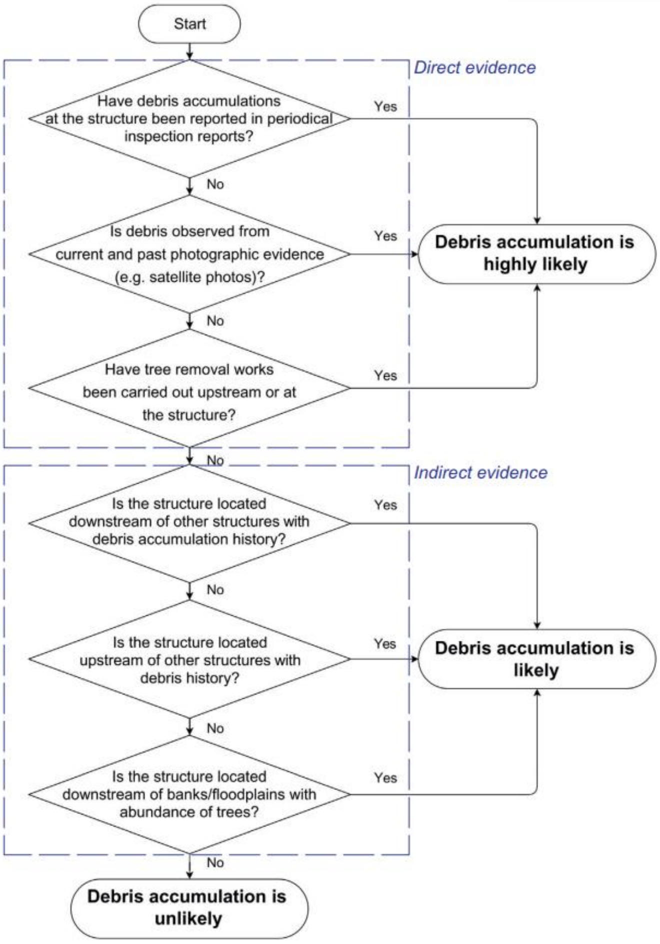

Figure 4.5 The proposed flow chart for assessing debris accumulation at bridge piers by (Panici et al., 2020)

4.5 Multiscale modelling

4.5.1 Subgrid modelling

Floodplain vegetation can be very heterogenous: a grass meadow can occur directly next to a dense willow patch or a row of hawthorns. This spatial variability usually has a smaller spatial scale [$\mathcal{O}(1\ \mathrm{m})$] than the computational grid ($\mathcal{O}(10\ \mathrm{m})$] of a hydraulic model. Consequently, a method is required to transform the measurable vegetation properties (size, density) to a representative roughness for a grid cell.

Extensive research on this topic has been done, e.g. by van Velzen et al. (2003), resulting in averaging methods that were – at the time – much more advanced than simpler methods based on textbook or calibrated roughness values and that matched available monitoring techniques. These averaging methods are used in the trachytope approach described in chapter 3.1.

However, this approach is arguably caught up by more advanced observation methods. A smaller grid cell size would (partially) alleviate this problem by letting the hydrodynamic equations do their work under actual flow conditions, but at considerable computational cost.

Subgrid modelling techniques are based on separating small-scale roughness and bathymetry effects on flow (these are not crucial for numerical stability) from the overall computational grid where Courant stability, or a proper momentum balance, is required (see Baltus (2022) for an example).

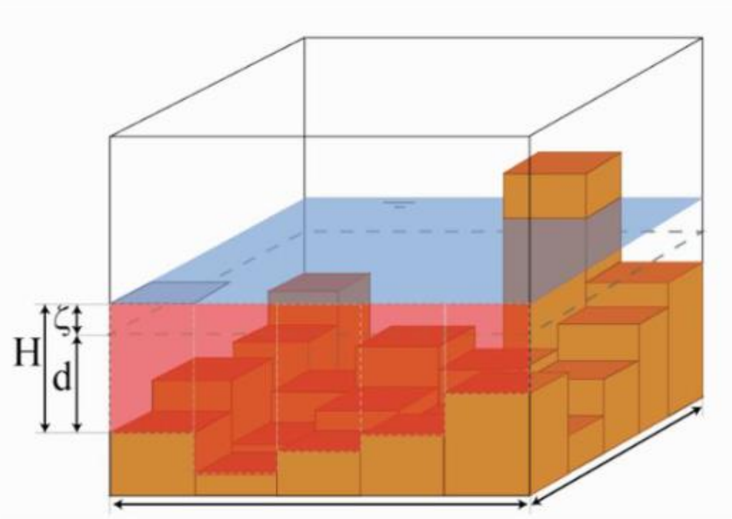

Figure 4.6 Example of a computational cell with higher resolution subgrid for bed levels. (Baltus, 2022)

Another consequence of the computationally necessary large grid cell size is the even distribution of roughness, flow velocity, bed shear stress and consequently erosion/deposition within a grid cell. Local dynamics, acting on scales of decimetres around individually establishing plants or metres around patches are spread out, creating a mismatch between the actual landscape dynamics and the model simplification. This is especially relevant in situations with strong spatial gradients, i.e. where plants just establish or are on the edge of a patch. To reproduce such complex biogeomorphological behaviour realistically over decadal timescales at reasonable computational cost, Antwerp University and NIOZ (Gourgue et al., 2018) have developed a convolution method on a subgrid level in their assessment of the development of the Hedwige-Prosperpolder.

4.5.2 Patch- and compound channel-scale

A limitation of current two-layer models is that they were derived from lab experiments that approximate 1D (or 2DV) flow. In applying these methods to models that have distributed vegetation, it is commonly assumed that these approaches can be upscaled to heterogeneous conditions. However, flow processes around and interaction between patches that affect roughness and deposition patterns may not be resolved by the hydrodynamic model explicitly (Meire, Kondziolka, and Nepf 2014; Marjoribanks et al. 2017; Berends et al. 2020).

On the scale of a compound channel, there is evidence of a significant exchange of momentum through large horizontal coherent structures (LHCS) between the main channel and floodplain that affect flow and transport processes beyond the vegetated areas (Truong et al., 2019; Truong & Uijttewaal, 2019). Therefore, vegetation patterns may significantly affect the distribution of discharge and mass (sediment, contaminants) between main channel and floodplains.

Field validation of methods to resolve the effect of vegetated flows are necessary but scarce (Groom & Friedrich, 2018). Some studies use water level measurements along the river axis to compare different approaches (e.g. Dalledonne, Kopmann, and Brudy-Zippelius 2019; Chaulagain et al. 2022). However, such validation approaches can potentially suffer from overdetermination – various configurations may produce valid water levels, but with varying discharge distribution between channel and floodplain. Direct measurements of the distribution of discharge can provide stronger evidence (e.g. see Huthoff et al. 2013).

The current lack of empirical support (i.e. measurements) on vegetated flow on smaller scale (patches, heterogeneous patterns) and larger scale (discharge distribution in compound channels) compounds the problem of testing of model improvements and should therefore be considered a major knowledge gap.

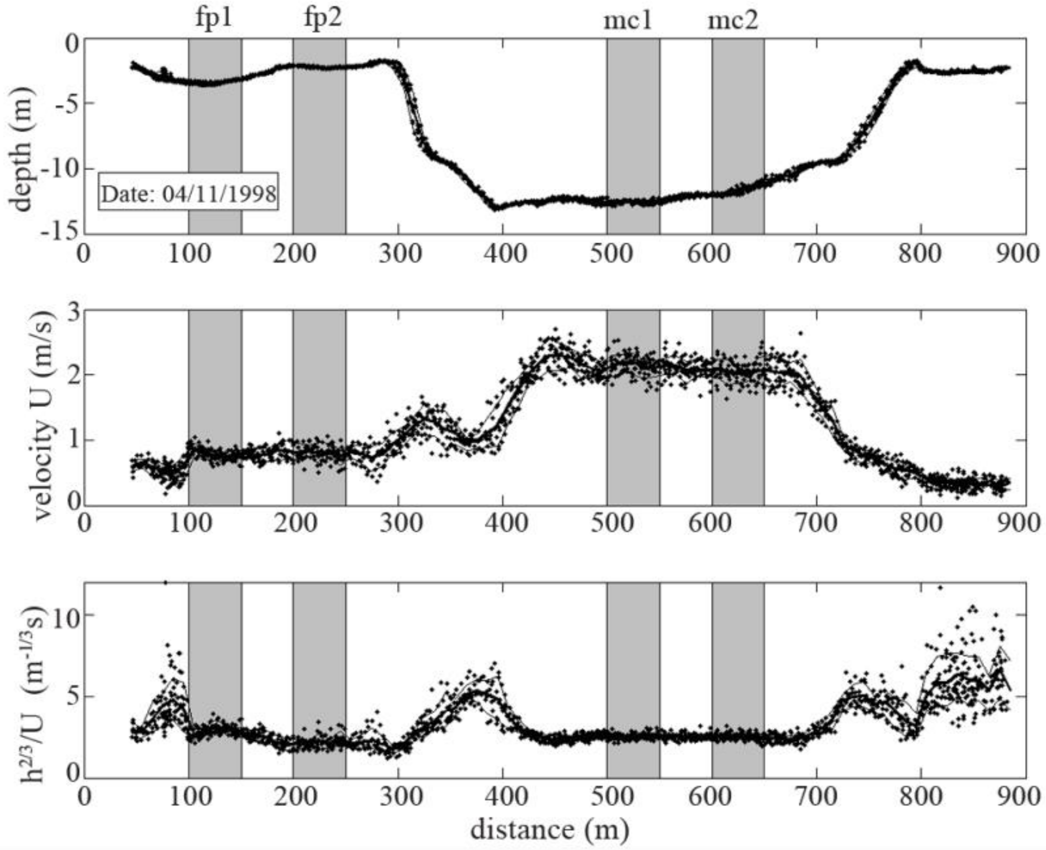

Figure 4.7 Measurements of the depth [sic], depth-averaged velocity and effective hydraulic resistance measured during the November 1998 flood on the river Rhine, upstream from the Pannerden bifurcation, using vessel-borne ADCP. At this section of the river the floodplains are uniformly covered with grassland. Image from (Huthoff et al., 2013)

4.6 Vegetation and model reliability

4.6.1 Model uncertainty

Uncertainty is a broad term with many different interpretations. In this section we follow the definition of uncertainty proposed by Berends, Diermanse, and De Jong (2021) in the context of river models of Rijkswaterstaat. In this definition, model uncertainty is defined as variability in model output due to imposed variation in its assumptions. If there is no imposed variation, there is no model uncertainty. It is contrasted with predictive uncertainty, which is defined at the statistical distribution of residuals between model output and measurements. Predictive uncertainty is closely related with model accuracy, while model uncertainty is closely related with model precision.

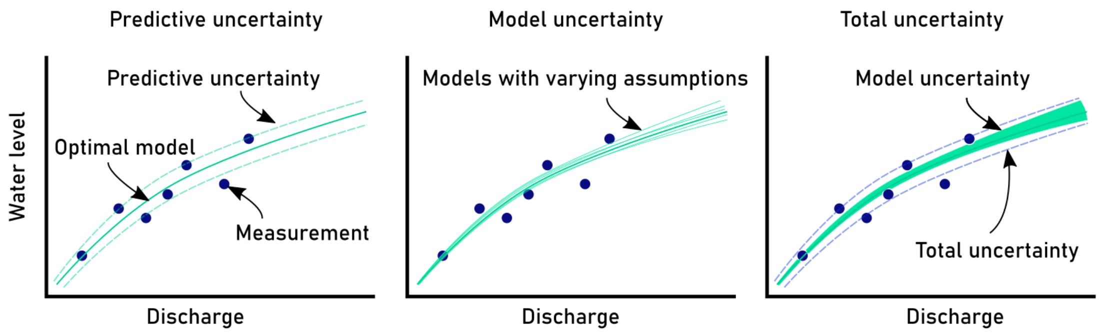

Figure 4.8 Illustration of the fitting of a curve through a dataset. In the left figure, the optimal (calibrated) model has no model uncertainty and the bounds show the predictive uncertainty – closely related to model accuracy. In the middle figure we see that if the model is optimized using varying assumptions (analogous to choosing more or less conservative values for vegetation in Figure 2.7), multiple 'optimal' models may be found. In the right we see that the total uncertainty encompasses the model uncertainty and predictive uncertainty. Adapted from Berends, Diermanse, and De Jong (2021)

In the case of Figure 2.7, there is no model uncertainty because both assumptions used a single value: an assumed value for vegetation roughness *k* and calibrated channel roughness. However, this is conditional on a single measurement. In statistical calibration[25], model uncertainty is reduced by doing additional measurements. This makes intuitively sense: more evidence leads to more certainty that a better model cannot be found. However, statistical calibration methods are computationally too demanding for practical use outside of a research setting.

One example of statistical calibration to determine vegetation roughness based on experimental measurements is given by Berends et al. (2020). They found that vegetation roughness may be determined by statistical calibration, but that the presence of undergrowth significantly increases the roughness predicted by Baptist et al. (2007).

In hydraulic models of the Dutch Rhine, vegetation parameters are considered one of the most uncertain parameters (Warmink 2011), including errors in ecotope and land cover maps (Straatsma et al., 2013) The choice of which two-layer vegetation resistance model to use adds relatively little uncertainty compared to uncertainty in parameters (Warmink, Straatsma, et al. 2013). At design discharges, model uncertainty is estimated at approximately 70 cm, primarily due to vegetation parameter uncertainty (Warmink, Straatsma, et al. 2013; Berends, Warmink, and Hulscher 2018). This range was obtained using uncalibrated models, but it is unknown whether calibration will significantly reduce these bands. Rating curve models calibrated on measurements suggest similar (or larger) ranges (Berends et al. 2021; Gensen et al. 2022).

Uncertainty in intervention modelling is in practice generally not considered, as it is commonly assumed that any uncertainty 'cancels out' (as noted by Mosselman 2018b). This assumption is not accurate (Berends, Warmink, and Hulscher 2018). The 90% confidence interval of the intervention effect was estimated to be up to 40% of the total effect depending on the type of intervention. Particularly changes to the land cover (i.e. vegetation maps) were shown to be a major source of uncertainty.

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[25] Specifically, we refer to Bayesian inference. In Bayesian statistics, the result of calibration is not a single value but rather a probability distribution that is conditional on initial assumptions (*prior beliefs*). If there is more evidence (measurements), the relative strength of the initial assumptions increases. For a more in-depth discussion on these calibration methods we refer to Stedinger et al. (2008).

4.6.2 Model validation

An important observation is that model uncertainty should be expected to dominate the total uncertainty at discharges increasingly higher than the highest one observed. In other words: there may be many different assumptions (e.g. vegetation model parameters) that lead to good results in the measured domain, but different extrapolation results. This principle can be extended to extrapolation in time: if the modelled system is non-stationary[26], good results during measured periods may not hold for future systems.

The purpose of model validation is to test model performance under different conditions than used during calibration. Klemeš (1986) argued to test models for extrapolation by splitting a dataset into low- and high-rainfall conditions. Thirel, Andréassian, and Perrin (2015) proposed a similar test to validate a model for non-stationarity. Berends, Diermanse, and De Jong (2021) proposed a combined framework specifically for hydraulic fluvial models. Based on a review of literature, they concluded that for the models of the Meuse, the expected error in extrapolation is twice as large as the error from non-stationarity. Model validation under nonstationary conditions and extrapolation may potentially be a tool to test the effect of nonstationary vegetation (e.g. seasonal vegetation) on water levels, and the effectiveness of potential improvements.

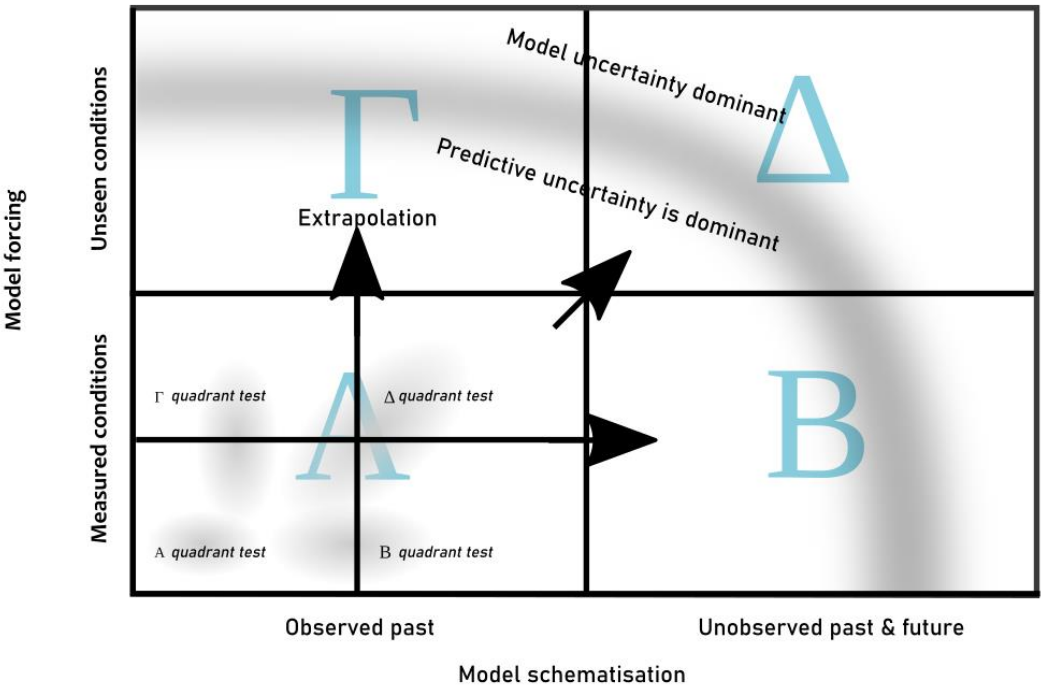

Figure 4.9 Proposed framework for testing fluvial models. The gamma quadrant test is similar to Klemeš (1986)*, the beta-quadrant test to* Thirel, Andréassian, and Perrin (2015)*. The delta-quadrant test is the most difficult to test for, but arguably the most important. Adapted from* Berends, Diermanse, and De Jong (2021)

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[26] Stationarity may refer both to the system being subject to change (because of anthropogenic and natural factors), and to the model being unable to cope with that change. In the latter sense, model non-stationarity manifests itself in an increasing model error over time. This is observed in models of Rijkswaterstaat.

5 Conclusion

5.1 What are the main principles to model vegetation in hydrodynamic models?

a *Which formulas, approaches or models are commonly used and what are the main differences between these models?*

b *What is the current practice within Rijkswaterstaat, what are the underlying assumptions or principles, and how does this relate to current practices from literature?*

The influence of vegetation on water levels is commonly resolved through modifying the flow resistance term (chapter 2.2). The Manning equation is most commonly used, even though this equation is not applicable to model flow through and over vegetation. Two-layer models are in theory superior to lumped equations like the Manning equation to resolve the roughness of vegetation. Various two-layer models are proposed. Most models compare favourably to lab experiments but may behave differently under field conditions.

Most national guidelines recommend using guidebooks and look-up tables to find a representative and auditable value for the Manning coefficient (section 3.2). Exceptions to this are Dutch (section 3.1.4) and German guidelines (section 3.2.4). Both recommend using a two-layer model (section 2.2.3). Only the German guidelines, which were published recently, recommend specific formulae to account for vegetation flexibility. Based on this selection we conclude that Rijkswaterstaat uses a methodology to resolve vegetation resistance that is state-of-the-art.

5.2 What is the merit of the critique on Rijkswaterstaat regarding vegetation modelling?

We identified three general lines of critique.

(1) There is more excess height than computations show, because of conservative assumptions in vegetation resistance formulations

Querner and Makaske (2011) argued that the use of the Klopstra model, in combination with the Van Velzen modification (see Appendix A.1) produces too high roughness values. Mosselman and van Velzen (2011) argued that the assumptions in the vegetation model used by Rijkswaterstaat were suitably chosen for the Dutch situation, and that calibration would greatly reduce the effect of any reasonable modification of that formula. The use of a different two-layer model will affect results, though likely marginally compared with using lumped Manning coefficients (paragraph 4.6.1). In this review, we have found that the Dutch guidelines are one of the few national guidelines that explicitly recommend using a two-layer model for vegetation roughness. In that sense, it should be considered state-of-the-art.

The choice whether or not to explicitly account for dynamic vegetation, e.g. by taking into account a certain excess height is ultimately political. The present models are not unnecessarily conservative considering the present state-of-the-art. However, if allowing for excess height for vegetation development becomes a management objective, Rijkswaterstaat is well positioned to take advantage of scientific advancement (also see reply to concern 3 below).

However, there is a case to be made to review the equations currently used. In particular, the Klopstra model is relatively complex (see appendix A.1) and (therefore) not commonly used and tested in international literature. Alternative models, in particular the model of Baptist et al. (2007) and to a lesser extent the model by Huthoff, Augustijn, and Hulscher (2007) have found more widespread adoption. Furthermore, both models have been extended to include terms for flexibility (e.g. see appendix A.4). Nevertheless, the Klopstra model is not more or less conservative than other two-layer models (see Figure 2.4).

The suggestion by Mosselman and van Velzen (2011) regarding the effect of model calibration merits some remarks. They argued that a change in the vegetation resistance formula would not be as pronounced as one may expect, because such a change requires a recalibration that negates this effect to a large extent. This argument is not wrong; but it is limited by the scope of that study. Their analysis did not consider the considerable uncertainty associated with calibration on a single high discharge event from almost 30 years ago (i.e. the 1995 / 1993 events; see section 4.6). For example - it may be more reasonable to instead calibrate on a more recent event, or a discharge that has been measured at multiple occasions. In that case, the extrapolated effect of a change in vegetation formulas is likely larger. However, it should be noted that methods to take into account these considerations in Rijkswaterstaat models are still being discussed (see section 4.6; Berends et al., 2021). Another limit to the scope of that debate is the focus on extreme water levels. Other applications, like effect studies for interventions focussed on change in vegetation cover, could be more affected. Therefore, it is recommended to explore the merit of improvements to vegetation formulas not (only) on model extrapolation studies, but based on bespoke validation strategies (see section 4.6; and recommendations in Berends et al., 2021) and, where possible, field measurements.

(2) The effect of seasonal vegetation is overestimated or too uncertain

The critique by Bureau Stroming (2021) was convincingly refuted by Schropp (2021). Previous analyses of the effect of seasonality of vegetation cover all agree that foliage can have a significant effect on water levels (section 4.3.3), which may be considered sufficient evidence to support current floodplain management within the confines of current policy frameworks. However, the scientific evidence on how much vegetation foliage contributes to an increase of water levels is limited. Both studies carried out (or commissioned) by Rijkswaterstaat (van Dongen, 2022; van Velzen & Jesse, 2005) note that measurement uncertainty prevents drawing definitive conclusions. At the moment all evidence of the effect of seasonality in Dutch rivers is model-based and remains to be validated by (field) measurements.

(3) There is no excess height, but it can be created at relatively little expense compared to the benefits it brings in terms of natural values

The online publication “Vertical Room for the River” (“Flows Productions” & “WWF,” 2021) proposed to create more dynamic nature by allowing an increase of 10 cm in key areas, i.e. where raising dikes is relatively inexpensive compared to e.g. dike relocation. However, a review of the technical reports underlying this publication suggest that (a) it is unclear how the proposed increase would translate into measurable ecological targets and (b) it is unlikely that an increase of 10 cm would be enough to meet the targets set by the national government (PAGW-Rivieren). In this context, it may be concluded that the goals set out by the government regarding the ecological development of the river system are (considerably) more ambitious than those set out by WWF.

Nonetheless, none of the reviewed guidelines (section 3.2), including those of The Netherlands, explicitly accounts for dynamic vegetation in its framework. Most guidelines recommend instead to model situations that are expected during flood conditions. In the Netherlands, for example, floods traditionally occur during winter conditions – for which relatively rigid vegetation without foliage is a defensible and logical assumption. An increased attention to summer floods, as well as the ecological ambitions set out in PAGW-Rivieren, make it increasingly important to consider vegetation in a more holistic way – considering both intra-annual and interannual development. Important associated topics are summer (flash) floods in combination with summer vegetation, as well as the effect of drought on vegetation dynamics (e.g. increased growth of willows).

One potential approach, proposed by Peters, Kater, and Geerling (2006) and Makaske et al. (2011), is to account for a buffer in the excess-height to allow for some natural processes. However, with the current state-of-the-art and evidence-base it is not straightforward to incorporate such a buffer in guidelines. Knowledge gaps include uncertainty regarding the effect of foliage (section 4.3.3), vegetation flexibility (section 4.2) and effect of land-cover change (section 4.6.1) on water levels, and limited field evidence on the discharge distribution between floodplain and main channel (section 4.5.2, 4.6.2). Nonetheless, Rijkswaterstaat is well-positioned to take advantage of scientific advancement in the coming decade, as will be explored in the next section.

5.3 Which scientific insights can lead to an improvement of the current practice?

a *How, and in which time frame, can these insights be incorporated in currently used models?*
b *What are the potential consequences for floodplain management and maintenance works within Rijkswaterstaat?*

Chapter 4 describes various trends in literature in detail. Here, we summarize these steps in a potential roadmap (Figure 5.1).

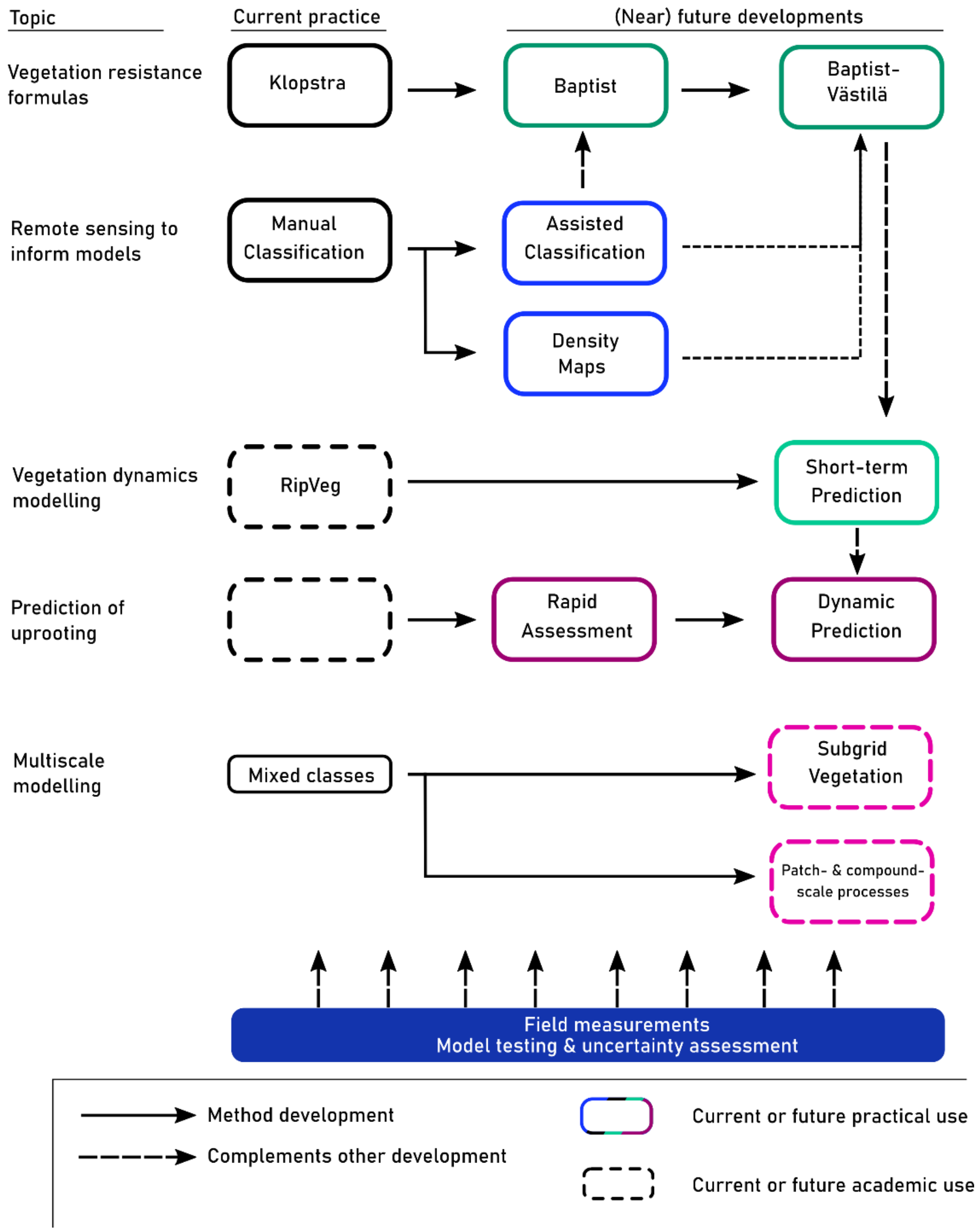

Figure 5.1 Roadmap for adoption of new trends in modelling guidelines for Rijkswaterstaat. Solid lines denote direct improvements. Dashed lines show potential synergy between improvements. Dashed boxed denote developments that are at the moment further removed from practice.

5.3.1 Vegetation resistance

Currently, Rijkswaterstaat models use the Klopstra formula to resolve vegetation resistance. To prepare for future trends, we recommend considering adopting the Baptist formula instead. This requires little change to current procedures, as this formula accepts almost the same parameter set[27], and is already implemented in D-HYDRO. Although the effects are relatively minor, it will likely require recalibration and will result in different results for design discharges. Previous studies (e.g. Warmink, Straatsma, et al., 2013) suggest a difference in the order of 12 cm at design discharge, but it is unknown whether it will be an increase or decrease of design water levels.

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[27] The only difference being that the Klopstra models uses Nikuradse roughness for bed resistance, while Baptist uses Chézy.

In the longer term, the modification of the Västilä-Baptist variant described in Appendix A.4 can be adopted. This formula is an incremental change to the Baptist formula and reduces to the traditional Baptist formula for rigid vegetation without flexibility. The improvement of this formula over the traditional Baptist equation is the addition of reconfiguration (flexibility) and the potential to use a (seasonal) leaf-area index (LAI) to account for foliage. However, additional research is required to (1) test the values and sensitivity of the reconfiguration parameters for vegetation native to the Dutch floodplains, (2) assess the use of LAI to inform the model parameters and (3) expand the formula to account for canopy deflection. Despite the need for further improvement, several case studies in literature use (a limited form of) this approach (see Dalledonne, Kopmann, and Brudy-Zippelius, 2019; Chaulagain et al. ,2022).

5.3.2 Remote sensing

Current ecotope maps are based on manual (human) classification of airborne images and come available approximately every 4-5 years. They inform hydraulic models by associating computational cells with a specific combination of vegetation parameters based on a look-up table. Advances in remote sensing, as well as vegetation resistance formulas, can potentially improve this practice in two ways.

First, classification of satellite images can be assisted by machine learning methods (see section 4.1.1) or other auxiliary information on management (see section 4.3.3) to increase the temporal resolution of ecotope maps[28], potentially updating the maps every year or every season. Well-established methods already exist and are in use by Rijkswaterstaat (*vegetatiemonitor*; see section 4.1.1) but are not used to inform hydraulic models. The potential application of assisted classification to inform hydraulic models requires an assessment of the required level of classification accuracy and establishing terms of acceptance for such methods. However, technical adoption into current hydraulic model pipelines should be relatively seamless, although the potential effect on model validation of a frequent update of roughness maps may require re-evaluation of model calibration and validation routines.

Second, remote sensing can inform models by incorporating measurements of vegetation density and biomass, either through photogrammetry (point clouds) or spectral methods (LAI, NDVI). The main advantages of this innovation are (1) to allow for spatial distribution of density and (2) to provide an approach to incorporate seasonal variation in density. This innovation is both technically and scientifically still being developed for large-scale application.

5.3.3 Vegetation dynamics

Vegetation dynamics – the study of growth, colonisation and decay of vegetation – is not currently applied in fluvial studies of Rijkswaterstaat. Various methods are proposed, some of which have published case studies with D-HYDRO (RipVeg and CR06). These methods are currently not mature enough to be considered for fluvial guidelines. In the future, however, potential applications may include short-term (e.g. a few years) prediction of the development of proposed interventions, in the context of ecological benefits and required excess height.

5.3.4 Uprooting

Uprooting refers to the removal and transport of vegetation by flow. Uprooting is currently not considered in the fluvial guidelines. In the short term, potential application may be found in rapid assessment of uprooting probability using critical flow velocity (see section 4.4.1), although such methods would require validation based on field observations for Dutch cases.

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[28] One may expect a decrease of manual labour as well, but this should be off-set against additional field work to verify the machine-learning classification.

Another potential application lies in vulnerability assessments of fluvial infrastructure to transport of woody debris, considering ambitions to increase the volume of herbaceous vegetation in the floodplains toward 2050 (PAGW-Rivieren; Heusden et al. 2021). Guidelines proposed in other countries, such as the UK, may offer a starting point for such efforts (see section 4.4.2).

5.3.5 Multiscale modelling

Multiscale modelling refers to subgrid approaches and accounting for patch and compound-channel scale processes that are not explicitly resolved by hydraulic models on a grid scale typically used in large-scale river models. In this report we briefly mentioned some recent work on these topics. Potential improvements in this field still require significant scientific study, and therefore no estimate of a timeline can be given.

5.3.6 Field measurements, model testing and uncertainty assessment

All above mentioned potential improvements benefit from field measurements, model testing and uncertainty assessment.

Field measurements are necessary to produce ground-truth for the validation of remote sensing methods, vegetation dynamics and uprooting models, and the discharge distribution between main channel and floodplain. A lack of empirical support (section 4.5.2) compounds the problem of testing models and model improvements. Going forward, it is recommended to make an inventory of the required data to support the future improvements set out in this report, and to incorporate this in a measurement plan that is linked to the hydraulic modelling pipelines.

An increasing attention to summer floods and ambitions to allow more dynamic nature should be supported by models that are validated for such purposes. The current set of hydraulic models has not been explicitly tested for these conditions (section 4.6.2; references therein). Adopting new approaches to calibrate and test models will help increase the confidence in their predictions to support floodplain management.

5.4 Recommendations

5.4.1 Close-to-practice improvements

Steps that are scientifically and technologically ready for implementation but may require additional testing or adaptation to fit within current guidelines are the adoption of the Baptist flow resistance formula and the use of computer-assisted classification maps to inform hydraulic models.

We advise to assess the impact on model results of switching to the Baptist equation for vegetation resistance, especially when extrapolating beyond calibrated (and measured) ranges of observed water levels and discharge. Such a study could address how to modify current handbook (*Stromingsweerstand vegetatie in uiterwaarden;* van Velzen, 2003*),* parameters, the effect of recalibration on discharge distribution between floodplain and main channel, predicted water levels and the assessment of intervention effects. Furthermore, we advise to formulate acceptance requirements for the accuracy of assisted classification maps. Assisted classification concerns methods that incorporate machine learning (e.g. *vegetatiemonitor,* see chapter 4.1) as well as other information (e.g. management plans, see chapter 4.3.3) with the aim of increasing the frequency of vegetation map updates.

5.4.2 Technological development

Steps that have a broad or growing scientific basis but require further technological development or specific Dutch case studies, are the use of remote sensing density maps and flow formulas that incorporate reconfiguration (flexible vegetation).

We advise a study of satellite derived density maps (e.g. based on the leaf-area index) for the Dutch rivers over a period of multiple years, with the aim of observing the long-term and seasonal trend in vegetation density. The results can already be compared to international literature, as well as to the current values in the national guideline (‘*Handboek vegetatieruwheid*’, Van Velzen, 2003). This study should provide insight in the applicability and feasibility of using satellite derived LAI-density maps, as well as the potential influence on model results. Building on this, we advise to study the potential benefit of using the Baptist-Västilä formula variant to model summer vegetation. Such a study should address the sensitivity of the reconfiguration parameters in Dutch rivers, and if necessary, derive parameter values specific to species characteristic to the Dutch floodplains. Finally, the sensitivity of, and potential candidates for canopy deflection models should be addressed.

5.4.3 Scientific demonstration

Steps that are proposed but require a broader evidence base in literature are rapid assessment of uprooting, subgrid vegetation representation and prediction of vegetation dynamics. Patch- and compound-scale processes are still being studied academically. To our knowledge, no potential candidate method to improve current practice has been proposed or tested.

While relatively simple uprooting models are proposed, to our knowledge evidence of uprooting is only anecdotally available. We advise to enquire with relevant regional experts what sites are known to be susceptible to uprooting after a significant flood, and to start logging evidence of uprooting, after a flood occurs through photographs and GIS maps. Such evidence is important to be able to validate future models. For multiscale modelling we advise to invest in upscaling current computer- or lab experiments to (near) field conditions. Water level measurements alone may not provide enough information to confidently validate method improvements. Field measurements, especially during floods, are invaluable to establish more confidence in extrapolating model results to unseen conditions.

References

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A Vegetation formulas

A.1 Klopstra formula for submerged flow

The Klopstra formula (Klopstra et al, 1997) for submerged flow reads

$$C = h^{-\frac{3}{2}}(T_1 + T_2 + T_3)$$

with

$$T_1 = \frac{2}{A_2}(\sqrt{C_3 \exp(h_v A_2) + u_v^2} - \sqrt{C_3 + u_v^2})$$

$$T_2 = \frac{u_v}{A_2} \log\left(\left(\sqrt{(C_3 \exp(h_v A_2) + u_v^2)} - u_v\right)\left(\sqrt{C_3 + u_v^2} + u_v\right)\left(\left(\sqrt{C_3 \exp(h_v A_2) + u_v^2} + u_v\right)\left(\sqrt{C_3 + u_v^2} - u_v\right)\right)^{-1}\right)$$

$$T_3 = \frac{\sqrt{g\big(h - (h_v - h_s)\big)}}{\kappa}\left(\big(h - (h_v - h_s)\big) \log \frac{h - (h_v - h_s)}{z_0} - h_s \log \frac{h_s}{z_0} - (h - h_v)\right)$$

and

$$z_0 = h_s \exp -F$$

$$F = \frac{\kappa \sqrt{C_3 \exp(h_v A_2) + u_v^2}}{\sqrt{g(h - (h_v - h_s)}}$$

$$h_s = g\left(1 + \sqrt{1 + \frac{4E^2\kappa^2(h - h_v)}{g}}\right)(2E^2\kappa^2)^{-1}$$

$$E = \frac{A^2 C^3 \exp(h_v A_2)}{2\sqrt{C_3 \exp h_v A_2} + u_v^2}$$

$$C_3 = \frac{2g(h - h_v)}{\alpha A_2(\exp h_v A_2 + \exp -h_v A_2)}$$

$$A_2 = \sqrt{2A}$$

$$A = \frac{m d C_d}{2\alpha}$$

$$u_v = \sqrt{u_v^2}$$

$$u_v^2 = \frac{h_v}{\frac{C_d h_v m d}{2g} + C_b^{-2}}$$

$$\alpha = 0.0227 h_v^{0.7}$$

where the formula for α is the modification by Van Velzen which was critized by (Querner & Makaske, 2011). α is an expression for the turbulent length scale for flow around cylinders.

A.2 Huthoff 2007 formula for submerged flow

The Huthoff formula (Huthoff et al, 2007) for submerged flow reads

$$C = U_{r0} U_v$$

With

$$u_v = \sqrt{\frac{h_v}{h} + \frac{h_s}{h}\left(\frac{h_s}{s}\right)^{Z}}$$

$$U_{r0} = \sqrt{\left(C_b^{-2} + \frac{C_D m D h}{2g}\right)^{-1}}$$

and

$$Z = \frac{2}{3}$$

$$h_s = h - h_v$$

$$s = \frac{1 - \sqrt{m} D}{\sqrt{m} - 1}$$

A.3 Pasche & Lindner 1982 formula

This formula for rigid emergent ($h > h_v$) vegetation reads:

$$C = \sqrt{C_B^{-2} + \frac{C_D m D h}{2g}}$$

Note that the Baptist equation is equivalent to the Pache & Lindner equation for emergent flow. A formula for C_D is proposed:

$$C_D = 1.31 C_{D\infty} u_r^2 + \frac{2}{Fr^2}(1 - h_r)$$

where h_r is the ratio of flow depth before and after flow around the cylinders. For practical purposes however, a C_D value of 1.5 is recommended.

A.4 Generalized Baptist equation for flexible vegetation

The generalized Baptist equation is a modification of the formula proposed by Baptist et al. (2007) by Berends (2021), and tested against laboratory experiments by Västilä et al. (*in preparation)*.

The formula is suitable for emergent and submerged flow and reads:

$$C = \left(C_b^{-2} + \frac{\phi}{2g}\right)^{-\frac{1}{2}} + \frac{\sqrt{g}}{\alpha_\kappa} \ln K$$

With relative submerged *K*, turbulence parameter α_κ and vegetation parameter ϕ. In the original formulation of Baptist et al. (2007), α_κ is equal to the von Karman constant κ and $\phi = C_D m D h_v$. Note that for emergent flow, the right-hand term of the equation equals zero, and the equation reduces to the Pasche and Lindner equation.

This formulation allows for various vegetation models. The default vegetation parameter models rigid cylinders:

$$\phi = C_D m D h_v$$

The Järvelä (2004a) estimator models flexible vegetation:

$$\phi = C_{D,\chi} \mathcal{L} \left(\frac{u_c}{u_\chi}\right)^{\chi}$$

With leaf area index $\mathcal{L}$ and species-specific parameters $C_{D,\chi}, \chi$. The (Västilä & Järvelä, 2014) estimator models foliated vegetation:

$$\phi = C_{D,\chi,F} n_F \left(\frac{u_c}{u_{\chi,F}}\right)^{\chi_F} + C_{D,\chi,S} n_S \left(\frac{u_c}{u_{\chi,S}}\right)^{\chi_S}$$

With the indices *F* and *S* referring to foliage and stem parameter respectively. Note that the generalized Baptist equation does not resolve the total resistance through bed shear stress. We refer to Berends (2021) and Västilä et al. (*in preparation)* for further details.

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